



Short-Baseline Neutrino Workshop  
Fermilab, May 12-14, 2011



Indiana University Center for Spacetime Symmetries

# Lorentz and CPT violation in neutrino oscillations



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Indiana University

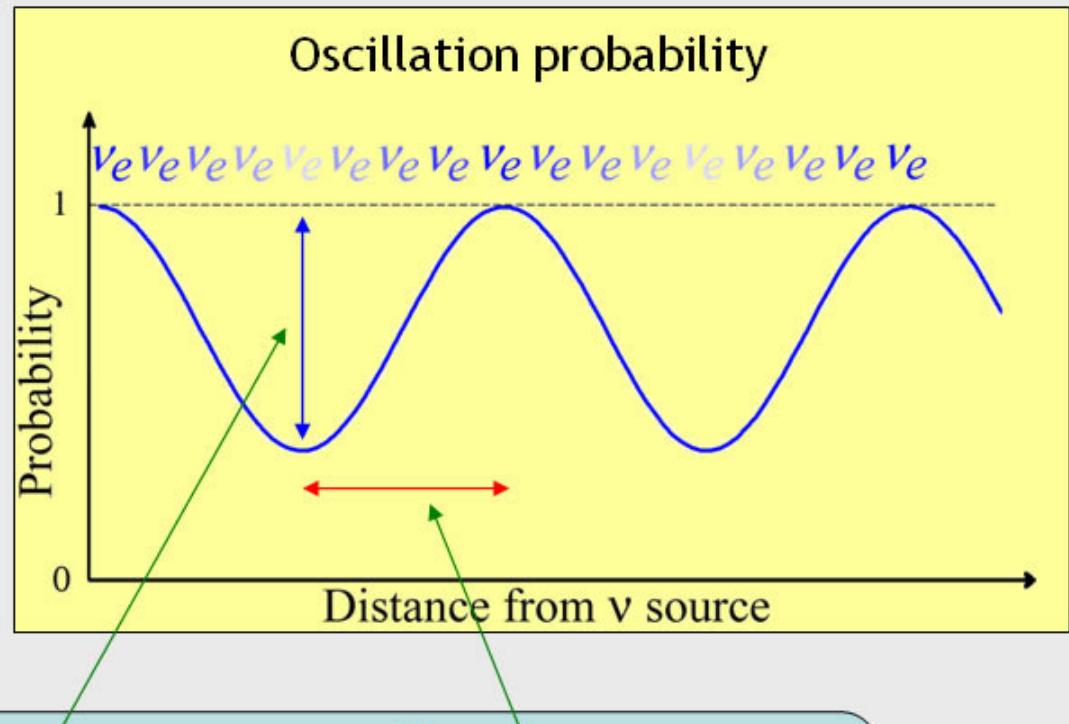
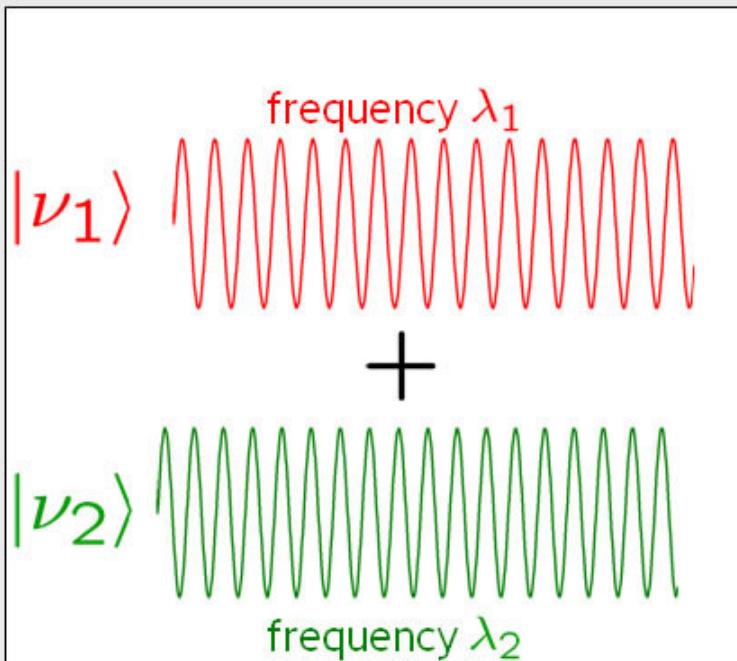
based on

JSD and V.A. Kostelecký, Phys. Lett. B 700, 25 (2011)  
(arXiv:1012.5985)

# Outline

- Neutrino oscillations
  - Experimental evidence
  - Three-neutrino massive model
- Lorentz and CPT violation
  - Motivation and framework: the Standard-Model Extension (SME)
- Lorentz-violating model for neutrino oscillations
  - Theory overview
  - Description experimental data and predictions
- Summary

# Neutrino Oscillations



$$P_{\nu_a \rightarrow \nu_b}(L) = \sum_{jk} A_{jk}(U) \sin^2(\Delta_{jk} L / 2)$$

$$\text{disappearance length: } L_{jk} = \frac{\pi}{\Delta_{jk}}$$

$$\Delta_{jk} = \lambda_j - \lambda_k$$

# Neutrino Oscillations: massive model ( $3\nu$ SM)

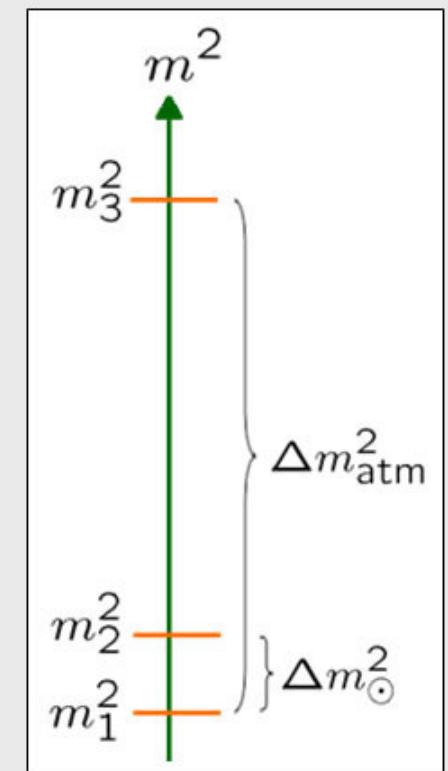
Effective hamiltonian

$$h_{\text{eff}} = \frac{1}{2E} U^\dagger \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m_\odot^2 & 0 \\ 0 & 0 & \Delta m_{\text{atm}}^2 \end{pmatrix} U$$

Properties:

- Lorentz and CPT invariant
- 3 massive neutrinos
- 6 (4) parameters
- Energy-independent mixing

$$U = \begin{pmatrix} c_{12} & -s_{12} & 0 \\ s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{13} & 0 & -s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & -s_{23} \\ 0 & s_{23} & c_{23} \end{pmatrix}$$



# Neutrino Oscillations: massive model ( $3\nu$ SM)

Effective hamiltonian

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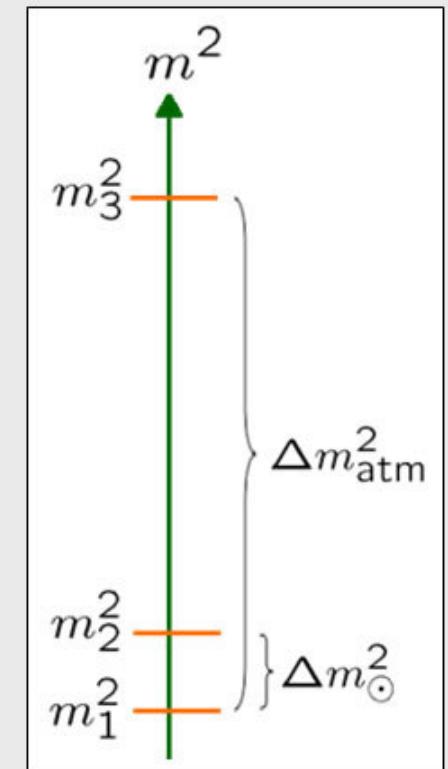
- Lorentz and CPT invariant
- 3 massive neutrinos
- 6 (4) parameters
- Energy-independent mixing

Two independent disappearance lengths

$$L_{21} = \frac{2\pi E}{\Delta m_\odot^2}$$

$$L_{31} = \frac{2\pi E}{\Delta m_{\text{atm}}^2}$$

$$P_{\nu_a \rightarrow \nu_b} \simeq \begin{cases} 1 - \sin^2 2\theta \sin^2 \left( \frac{\Delta m^2 L}{4E} \right) & , \quad a = b \\ \sin^2 2\theta \sin^2 \left( \frac{\Delta m^2 L}{4E} \right) & , \quad a \neq b \end{cases}$$



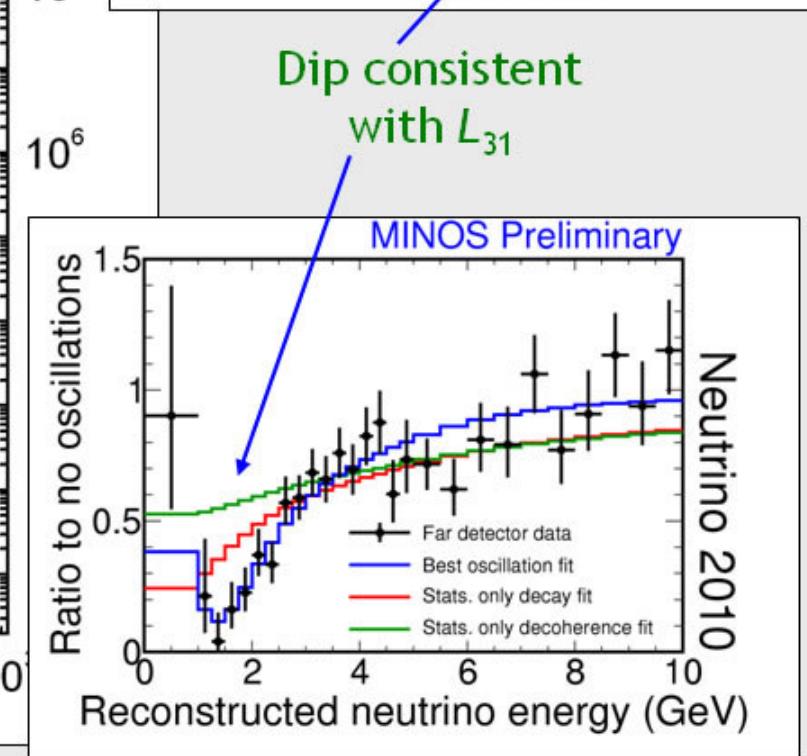
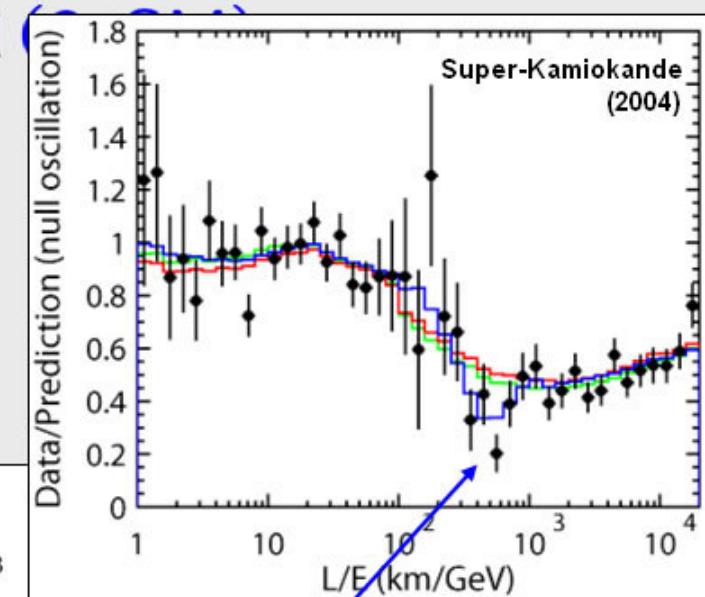
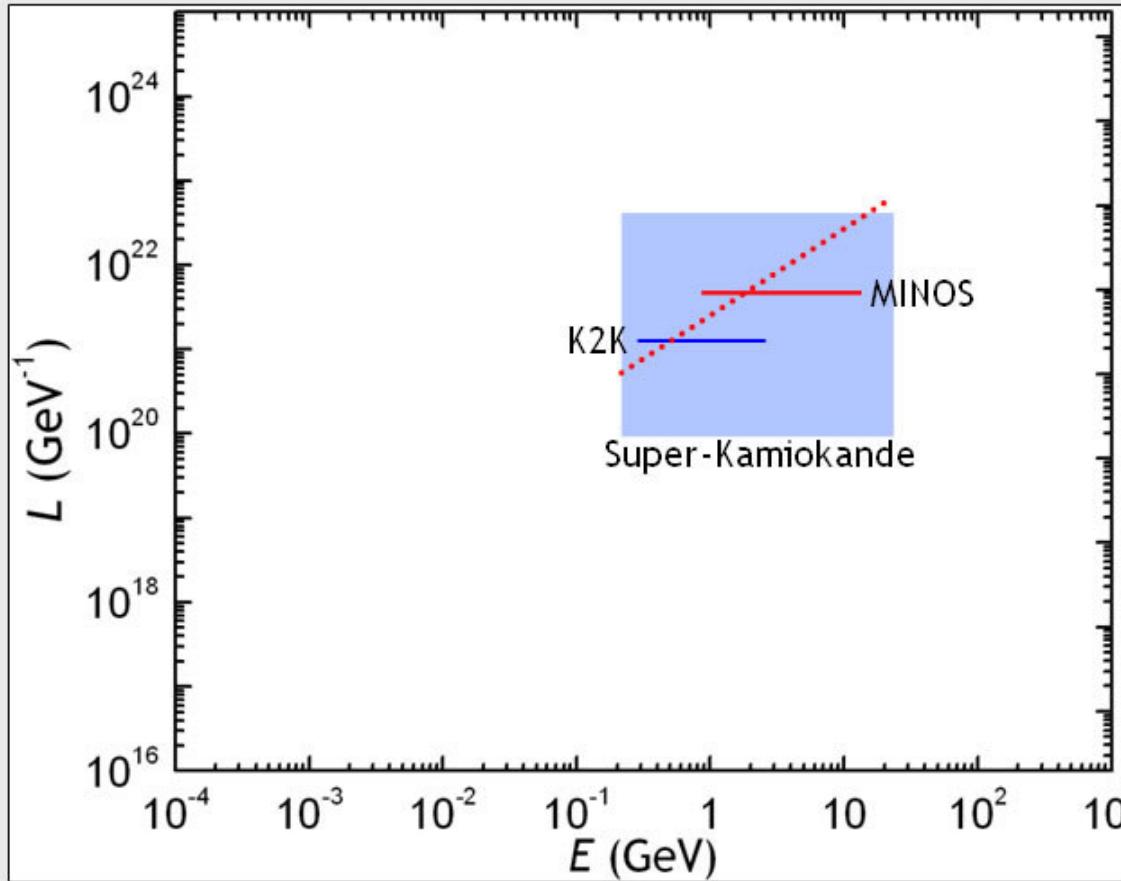
# Neutrino Oscillations: massive model

Two independent disappearance lengths

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KM plot: Kostelecky & Mewes, PRD (2004)



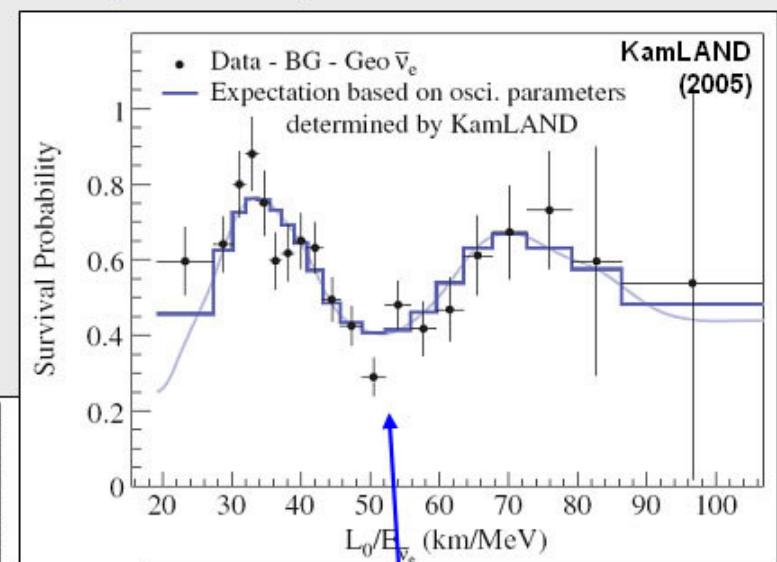
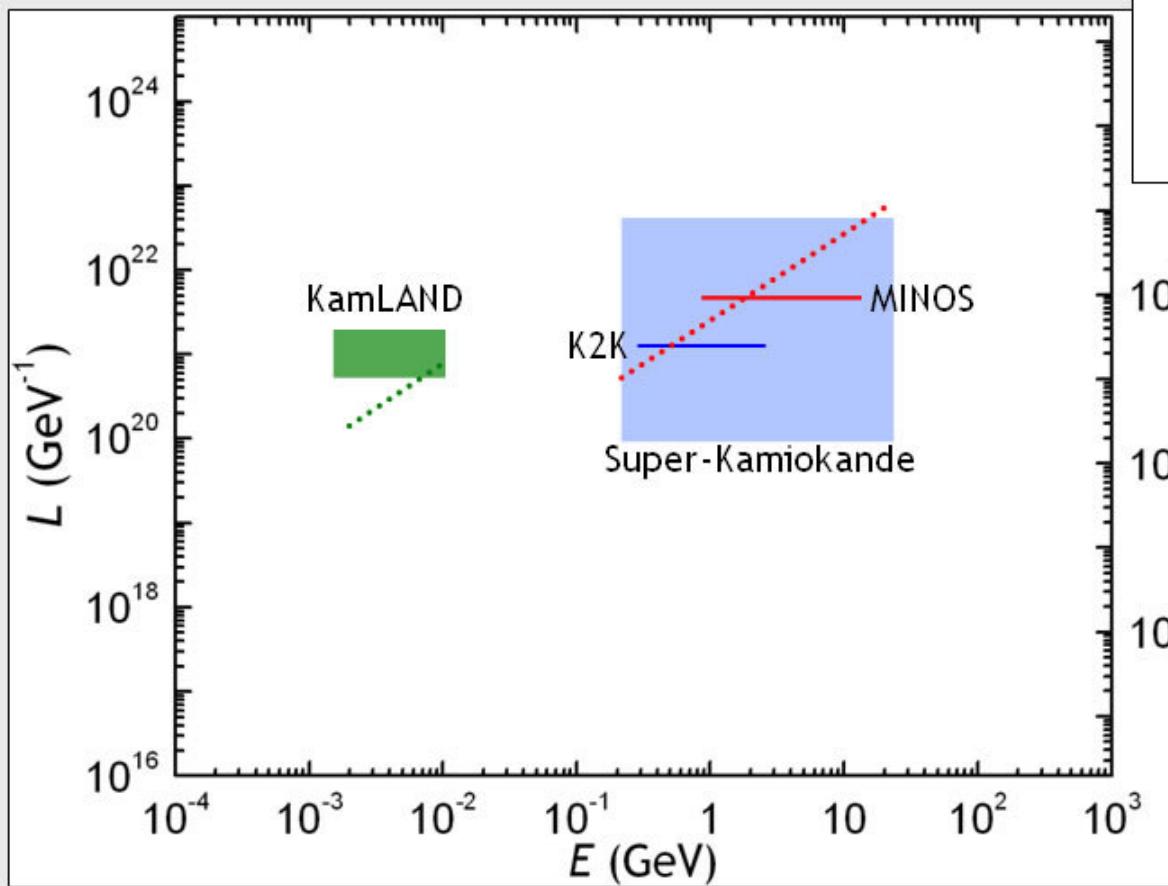
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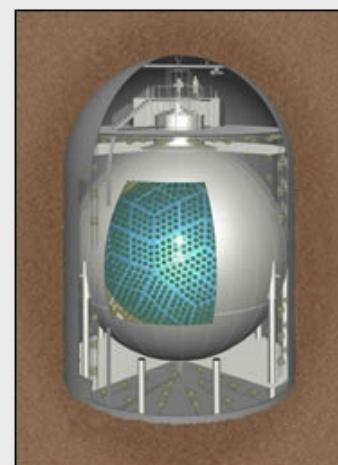
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oscillatory signature  
consistent with  $L_{21}$



KamLAND

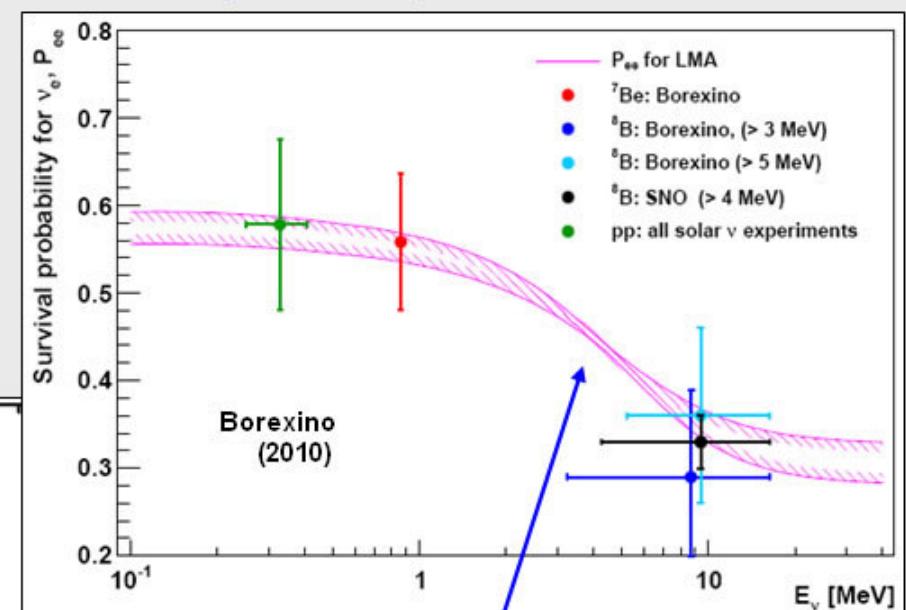
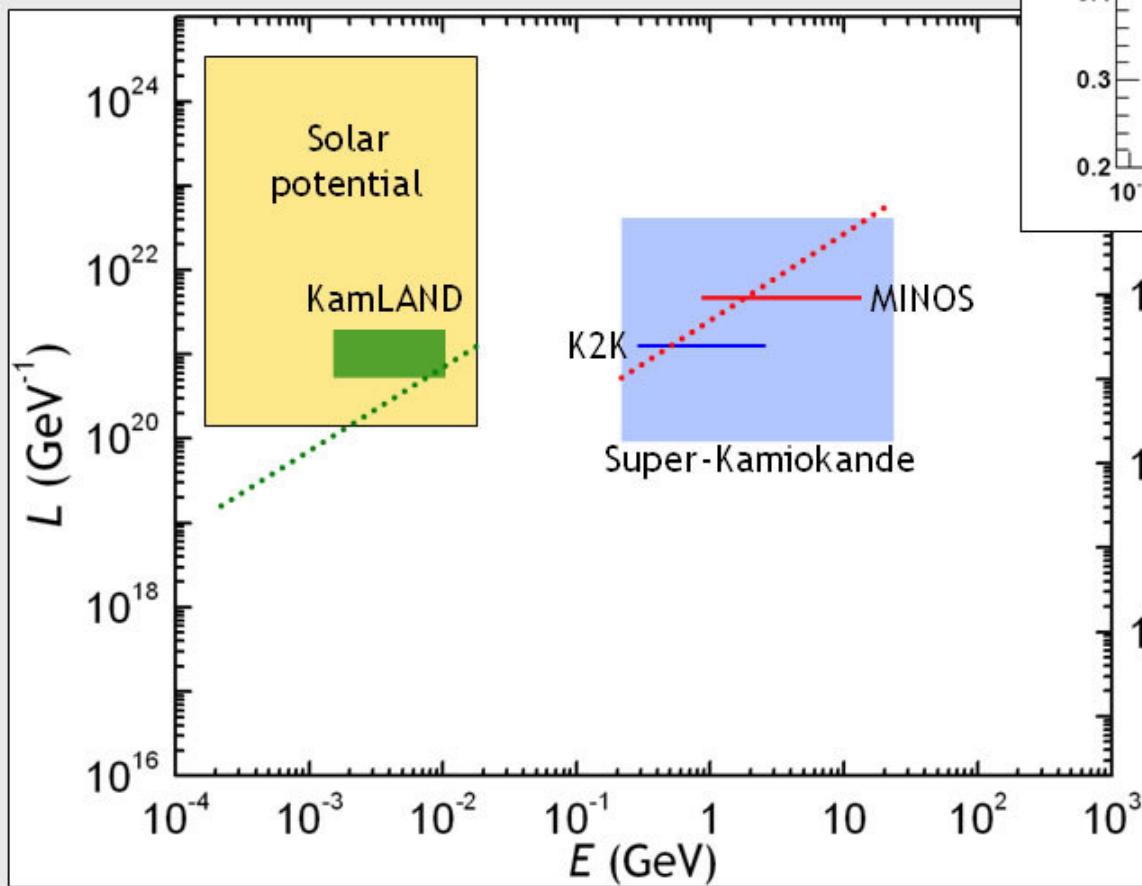
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enhanced effect consistent with solar potential and  $L_{21}$

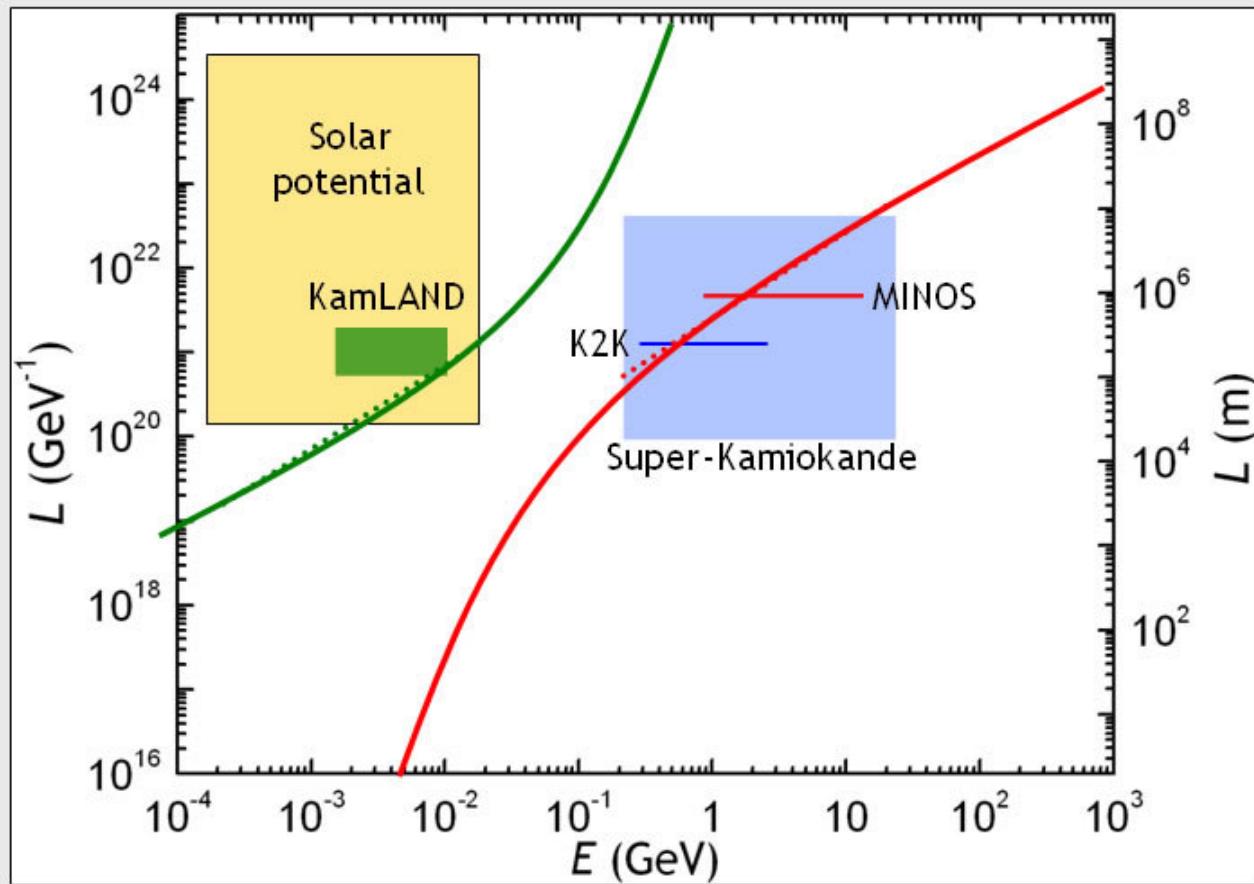
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We could try a more general function of the energy

$$L_{ij} = f(E)$$

10

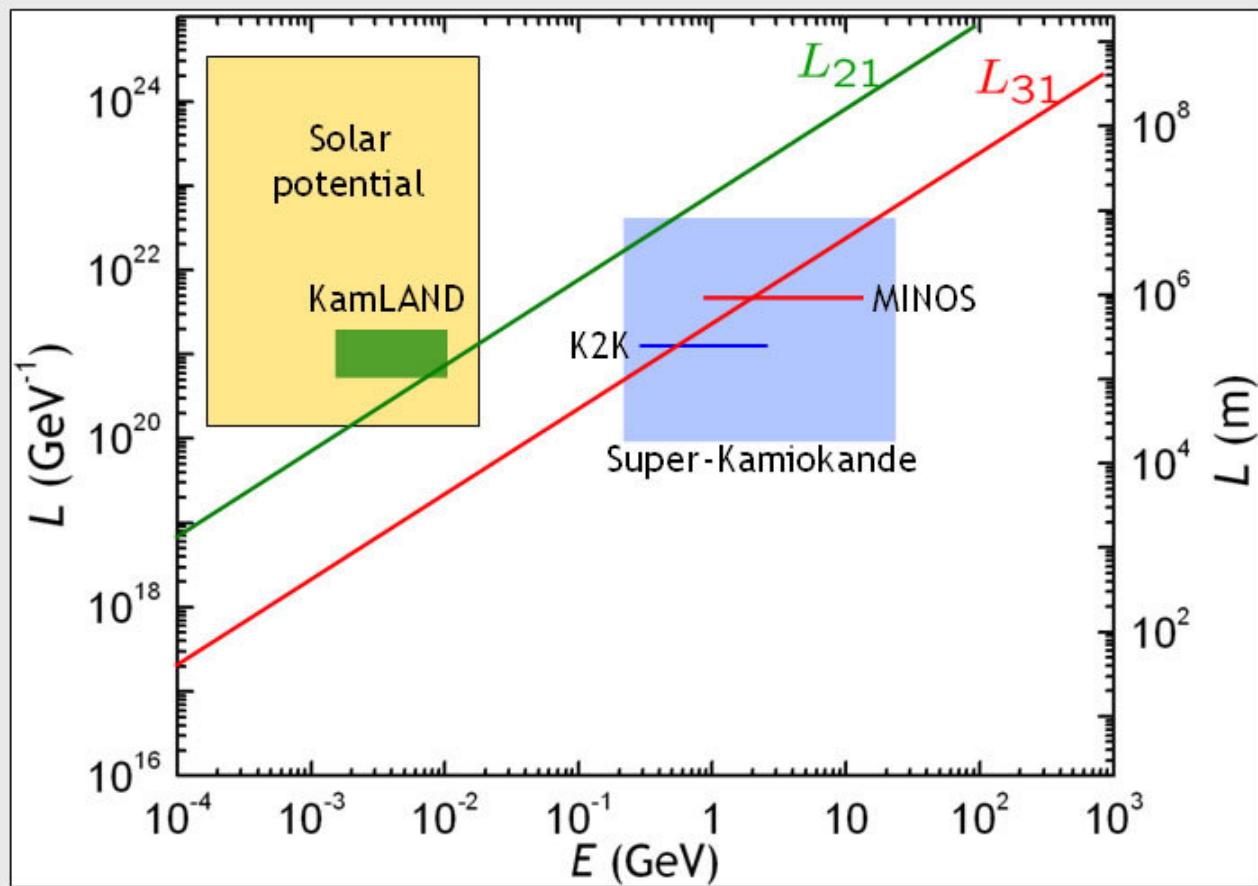
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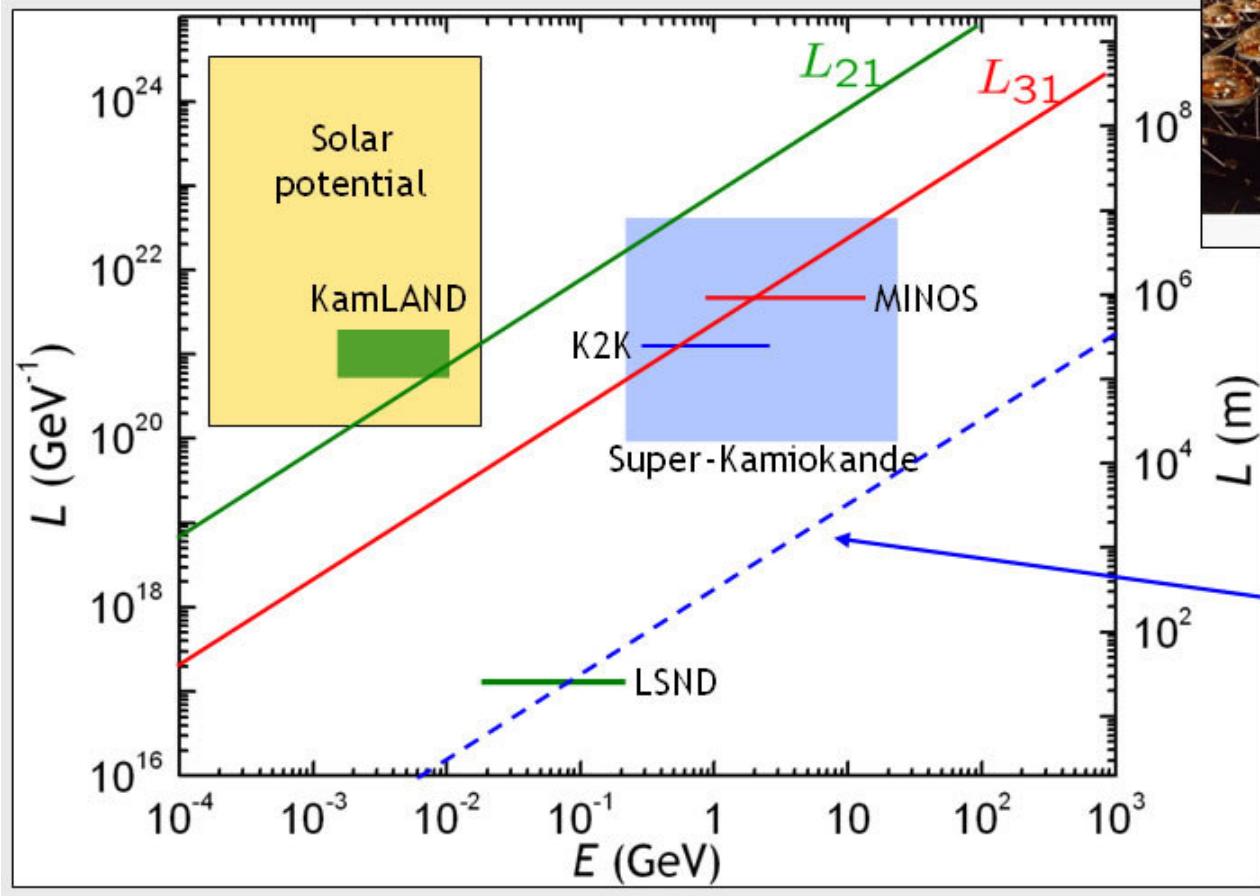
$$L_{ij} = f(E)$$

Lorentz invariance requires  
 $L_{ij} \propto E$

# Neutrino Oscillations: anomalies

LSND (2001)

3.8 $\sigma$  evidence of oscillations  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$



DNP

this line would require extra neutrino flavors (sterile neutrinos)

# Neutrino Oscillations: anomalies

MiniBooNE (2007,2010)

$$\nu_\mu \rightarrow \nu_e$$

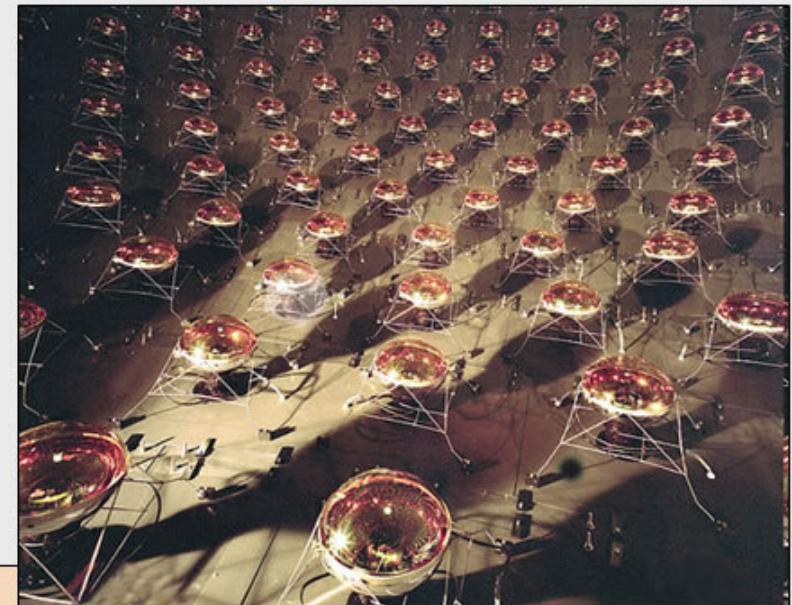
Neutrinos (2007):

- $E < 475$  MeV: unexplained  $3.0\sigma$  excess
- $E > 475$  MeV: no signals of oscillations

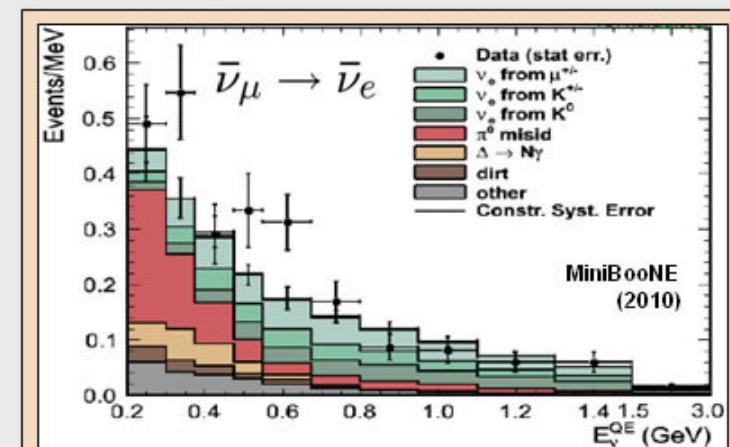
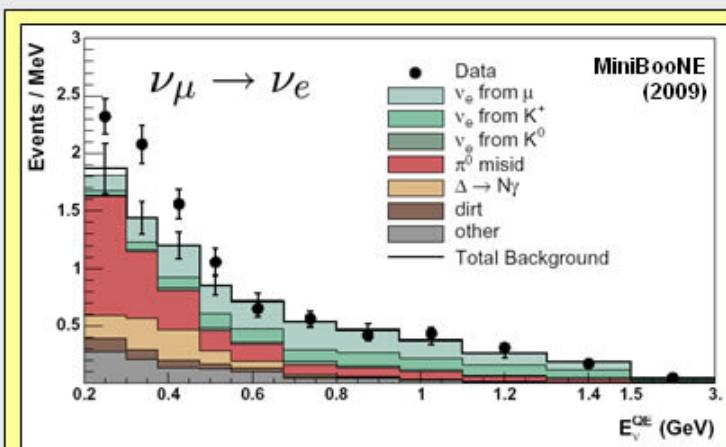
$$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$$

Antineutrinos (2010):

- $E < 475$  MeV:  $1.3\sigma$  excess
- $E > 475$  MeV: signal consistent with LSND (99.4%CL)



MiniBooNE



# Neutrino Oscillations: anomalies

MiniBooNE (2007,2010)

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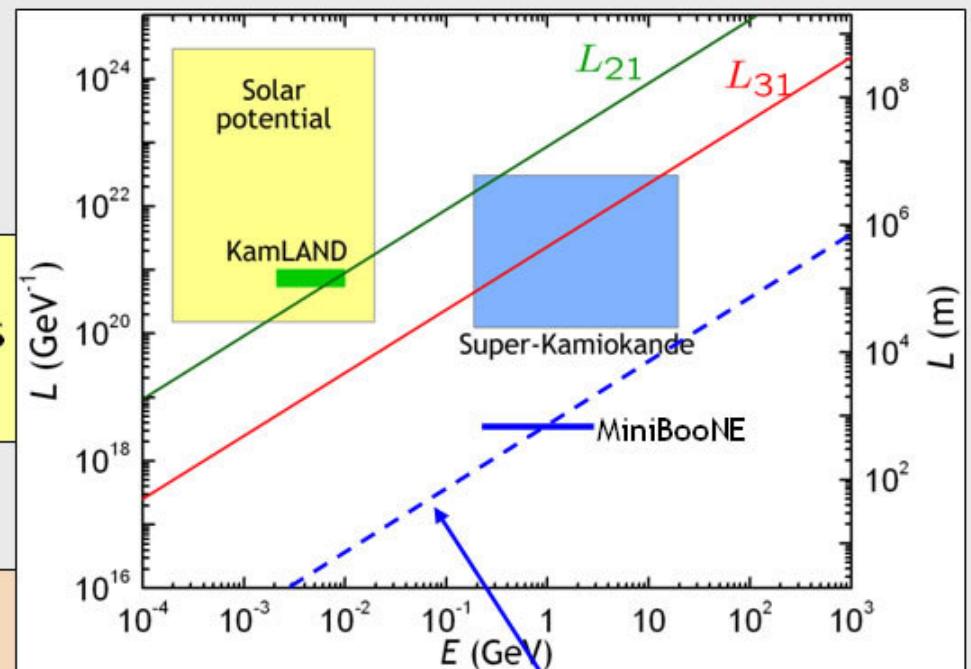
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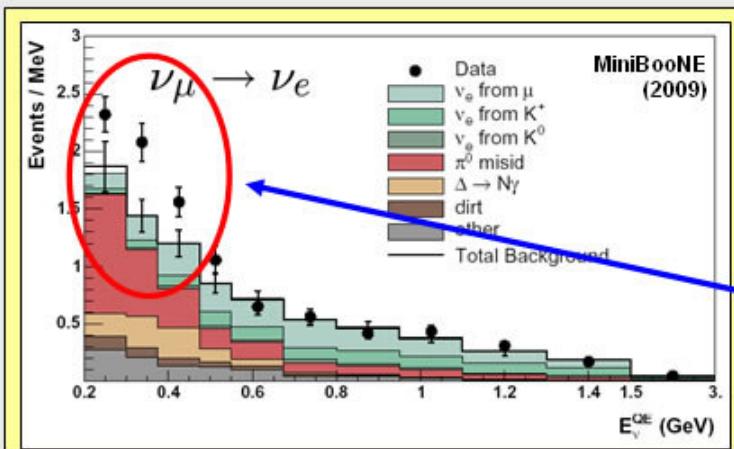
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sterile neutrinos

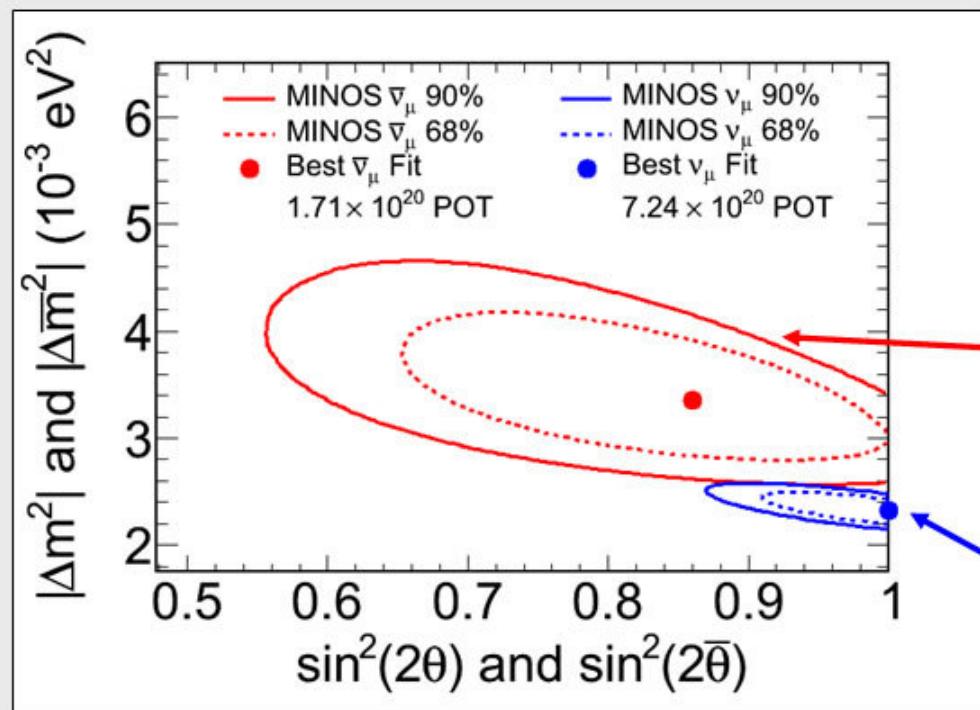


low-energy excess hard to  
explain using sterile neutrinos

# Neutrino Oscillations: anomalies

MINOS (2010)

Preliminary data suggest within the  $3\nu$ SM oscillation parameters for neutrinos and antineutrinos are not equal



MINOS

antineutrinos

neutrinos

# Neutrino Oscillations: results summary

## Compelling data

$3\nu\text{SM}$

|                       |  |  |
|-----------------------|--|--|
| Atmospheric neutrinos | Maximal disappearance of $\nu_\mu$<br>$L/E$ oscillation signature                                    |  |
| Reactor antineutrinos | Disappearance of $\bar{\nu}_e$ at large distances<br>(hundreds of km)<br>$L/E$ oscillation signature |  |
| Solar neutrinos       | Disappearance of solar $\nu_e$<br>MSW-LMA signature (matter effects)                                 |  |

## Anomalies

|                |                      |  |
|----------------|----------------------|--|
| LSND           | Oscillation signal   |  |
| MiniBooNE 2007 | Low-energy excess    |  |
| MiniBooNE 2010 | $\nu \neq \bar{\nu}$ |  |
| MINOS          | $\nu \neq \bar{\nu}$ |  |

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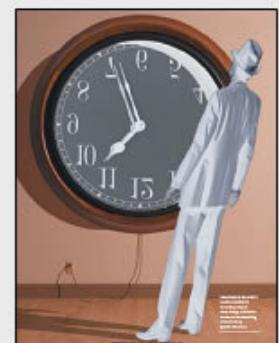
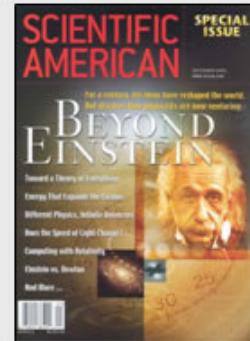
## Lorentz violation

Last 20 years, growing interest in the possibility that Lorentz symmetry may not be exact.

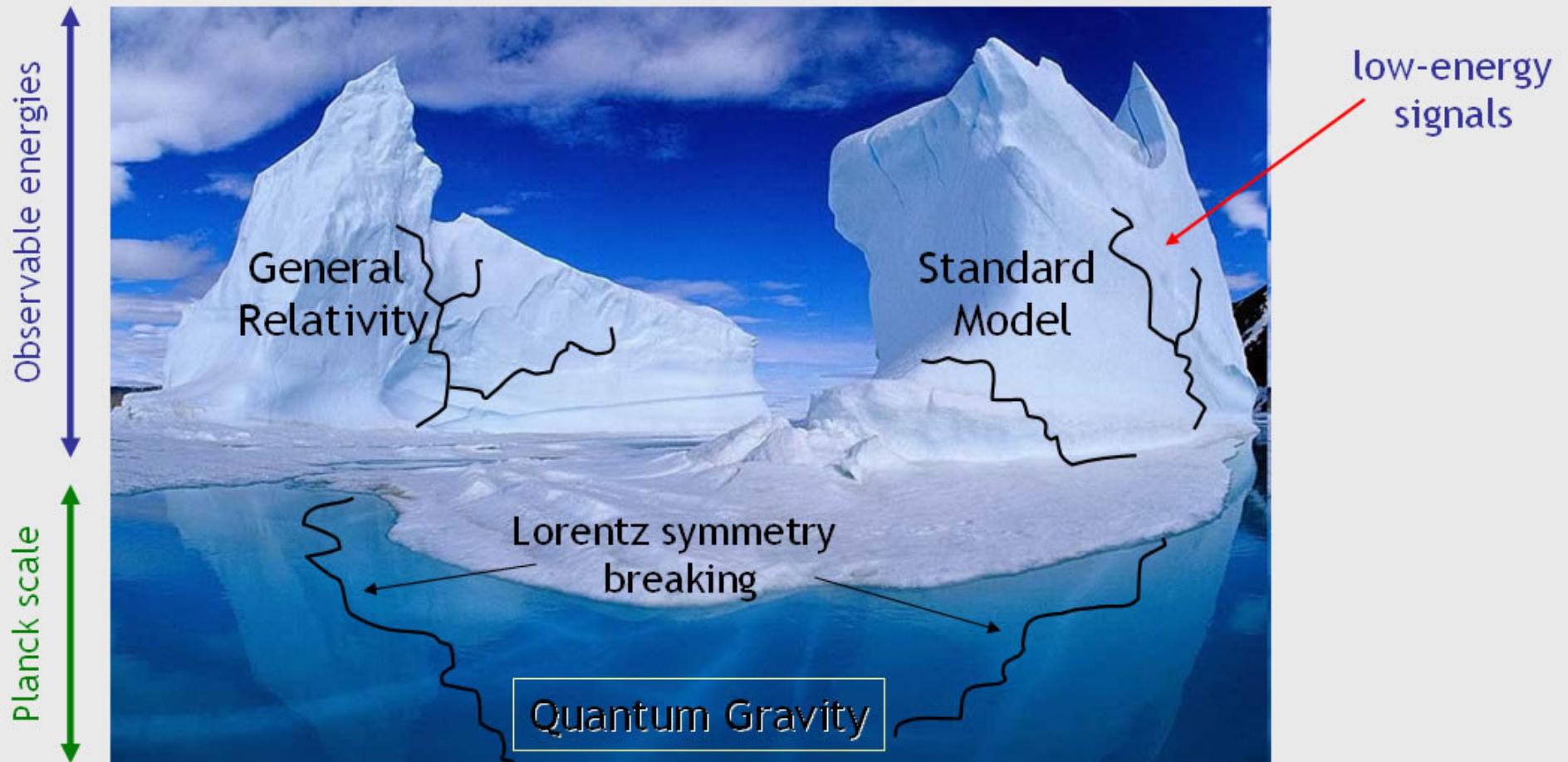
- Many candidates to explain quantum gravity involve the breaking of Lorentz symmetry: string theory, loop-quantum gravity, non-commutative field theories, ...

Kostelecký & Samuel, PRD 1989  
Kostelecký & Potting, NPB 1991

- Lorentz symmetry is a basic building block of both General Relativity (GR) and the Standard Model (SM). Anything this fundamental should be tested.



## Lorentz violation



- Observable signals of Lorentz violation can be described using effective field theory (Kostelecký & Potting, PRD 1995)
- Framework describing possible violations of Lorentz symmetry needed

## Standard-Model Extension

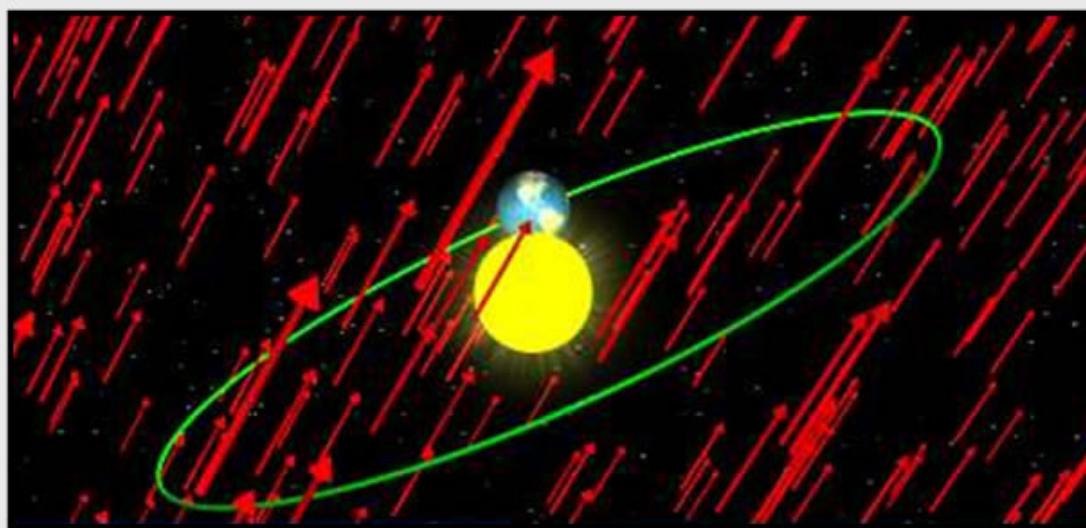
Colladay & Kostelecký, PRD 1997  
Colladay & Kostelecký, PRD 1998  
Kostelecký, PRD 2004

Standard-Model  
Extension

=

Standard Model  
coupled to Gravity

+  
all possible  
Lorentz violations



- Standard fields
- Controlling coefficients
- Observer scalars
- CPT violation included  
(no  $\Delta m^2 \neq \Delta \bar{m}^2$  terms)

$$\mathcal{L}_{\text{LV}} \supset a_\mu \bar{\psi} \gamma^\mu \psi$$

## Robustness of the SME

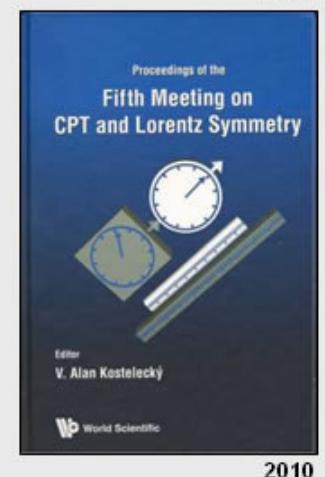
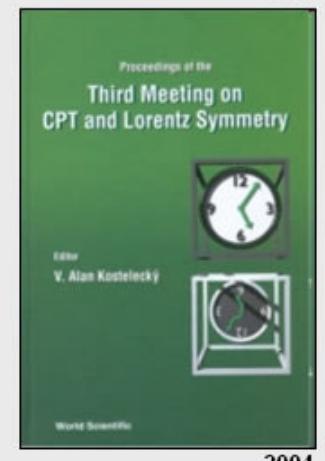
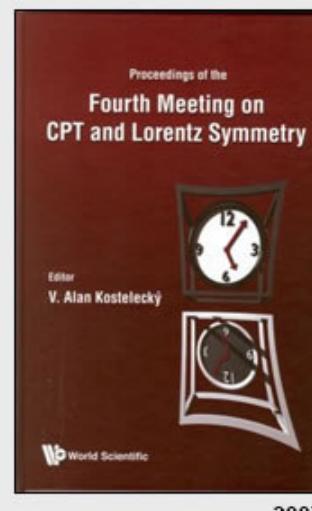
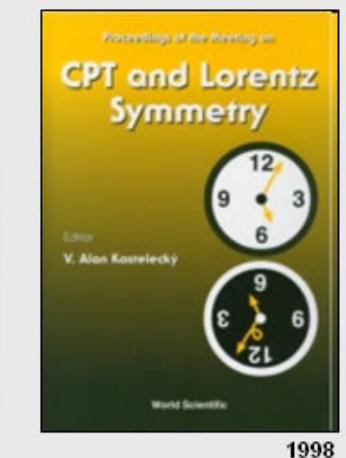
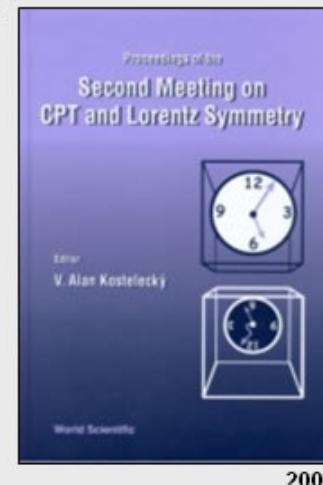
- structure of the Standard Model is preserved
  - $SU(3) \times SU(2) \times U(1)$  gauge structure
  - $SU(2) \times U(1)$  breaking
  - energy-momentum conservation
- based on quantum field theory
  - quantization methods
  - positivity of energy
- general framework for studying possible breaking of Lorentz symmetry
- experimental results across different disciplines can be related in a physically meaningful way
- tells what effect to look for in a given experiment

## SME: theoretical and experimental playground

Searches for CPT and Lorentz violations involve:

- neutrino oscillations
- oscillations and decays of K, B, D mesons
- particle-antiparticle comparisons
- matter interferometry
- birefringence and dispersion from cosmological sources
- clock-comparison measurements
- CMB polarization
- collider experiments
- electromagnetic resonant cavities
- equivalence principle
- gauge and Higgs particles
- high-energy astrophysical observations
- laboratory and gravimetric tests of gravity
- post-newtonian gravity in the solar system and beyond
- second- and third-generation particles
- space-based missions
- spectroscopy of hydrogen and antihydrogen
- spin-polarized matter

There are now more than  
1000 papers on the SME



# SME: worldwide searches

## K<sup>0</sup>-K<sup>0</sup> oscillations

- KLOE collaboration, A. DiDomeico et al., *Found. Phys.* **40**, 852 (2010);
- KLOE collaboration, A. DiDomeico et al., *J. Phys. Conf. Serv.* **171**, 012008 (2009);
- KLOE collaboration, M. Testa et al., *arXiv:0805.1968* (2008);
- KTeV collaboration, H. Nguyen et al., in *CPT and Lorentz Symmetry II* (2002);
- KTeV collaboration, Y.B. Hsiung et al., *Nucl. Phys. Proc. Suppl.* **86**, 312 (2000).

## D<sup>0</sup>-D<sup>0</sup> oscillations

- FOCUS collaboration, J. Link et al., *Phys. Lett. B* **556**, 7 (2003);  
FOCUS collaboration, R. Gardner et al., in *CPT and Lorentz Symmetry II* (2002).

## B<sup>0</sup>-B<sup>0</sup> oscillations

- BaBar collaboration, B. Aubert et al., *Phys. Rev. Lett.* **100**, 131802 (2008);  
BaBar collaboration, B. Aubert et al., *preprint SLAC-PUB-12003* (July 2006);  
BaBar collaboration, B. Aubert et al., *Phys. Rev. D* **70**, 012007 (2004);  
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OPAL collaboration, R. Ackerstaff et al., *Z. Phys. C* **76**, 401 (1997);  
DELPHI collaboration, M. Feindt et al., *preprint DELPHI 97-98 CONF 80* (1997).

## Gravity sector

- M.A. Hohensee, S. Chu, A. Peters, and H. Mueller, *arXiv:1102.4362* (2011);
- D. Bennet et al., in *CPT and Lorentz Symmetry V* (2011);
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- J.B.R. Battat, J.F. Chandler, and C.W. Stubbs, *Phys. Rev. Lett.* **99**, 241103 (2007).

## Tests with a spin-polarized torsion pendulum

- B. Heckel et al., *arXiv:0808.2673* (2008);  
B. Heckel et al., *Phys. Rev. Lett.* **97**, 021603 (2006);  
L.-S. Hou et al., *Phys. Rev. Lett.* **90**, 201101 (2003);  
B. Heckel et al., in *CPT and Lorentz Symmetry II* (2002).

## Muon sector

- BNL g-2 collaboration, G.W. Bennett et al., *Phys. Rev. Lett.* **100**, 091602 (2008);  
V.W. Hughes et al., *Phys. Rev. Lett.* **87**, 111804 (2001);  
BNL g-2 collaboration, M. Deile et al., in *CPT and Lorentz Symmetry II* (2002).

## QED tests in Penning traps

- H. Dehmelt et al., *Phys. Rev. Lett.* **83**, 4694 (1999);  
R. Mittleman et al., *Phys. Rev. Lett.* **83**, 2166 (1999);  
G. Gabrielse et al., *Phys. Rev. Lett.* **82**, 3198 (1999).

**Data Tables for Lorentz and CPT Violation,  
Kostelecký & Russell, Rev. Mod. Phys. (2011).**

## Neutrino oscillations

- MiniBooNE Collaboration, T. Katori, in *CPT and Lorentz Symmetry V* (2011);
- IceCube Collaboration, R. Abbasi et al., *Phys. Rev. D* **82**, 112003 (2010);
- MINOS Collaboration, P. Adamson et al., *Phys. Rev. Lett.* **105**, 151601 (2010);  
MINOS Collaboration, P. Adamson et al., *Phys. Rev. Lett.* **101**, 151601 (2008);  
LSND Collaboration, L.B. Auerbach et al., *Phys. Rev. D* **72**, 076004 (2005).

## Photon sector

- S. Parker et al., *arXiv:1102.0081* (2011);
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- M.A. Hohensee et al., *Phys. Rev. D* **82**, 076001 (2010);
- J.-P. Bocquet et al., *Phys. Rev. Lett.* **104**, 241601 (2010);  
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M. Tobar et al., *Phys. Rev. D* **80**, 125024 (2009);  
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M. Hohensee et al., *Phys. Rev. D* **75**, 049902 (2007);  
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J.P. Cotter and B.T.H. Varcoe, *physics/0603111* (2006);  
P. Antonini et al., *Phys. Rev. A* **72**, 066102 (2005);  
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P. Antonini et al., *Phys. Rev. A* **71**, 050101 (2005);  
M. Tobar et al., *Phys. Rev. D* **71**, 025004 (2005);  
P. Wolf et al., *Phys. Rev. D* **70**, 051902 (2004);  
P. Wolf et al., *Gen. Rel. Grav.* **36**, 2352 (2004);  
H. Mueller et al., *Phys. Rev. D* **68**, 116006 (2003);  
H. Mueller et al., *Phys. Rev. Lett.* **91**, 020401 (2003);  
J. Lipa et al., *Phys. Rev. Lett.* **90**, 060403 (2003).

## Clock-comparison experiments

- C. Gemmel et al., *Phys. Rev. D* **82**, 111901 (R) (2010);
- K. Tullney et al., in *CPT and Lorentz Symmetry IV* (2010);
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T.W. Kornack, G. Vasilakis, and M. Romalis, in *CPT and Lorentz Symmetry IV* (2008);  
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P. Wolf et al., *hep-ph/0509329* (2005);  
P. Wolf et al., *physics/0506168* (2005);  
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M.A. Humphrey et al., *Phys. Rev. A* **68**, 063807 (2003);  
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## SME: the neutrino sector

Kostelecký & Mewes (PRD 2004a)  
Kostelecký & Mewes (in preparation)

Effective hamiltonian for neutrinos (3x3 matrix) ← three left-handed neutrinos

$$(h_{\text{eff}})_{ab} = \frac{1}{2E} (\tilde{m}^2)_{ab} + \sum_{d \text{ odd} \geq 3} a_{ab}^{(d)} E^{d-3} + \sum_{d \text{ even} \geq 4} c_{ab}^{(d)} E^{d-3}$$

$a, b = e, \mu, \tau$

Lorentz invariant

CPT odd

Lorentz violating

CPT even

Build models based on this general effective hamiltonian

- bicycle model (Kostelecký et al., 2004)
- tandem model (Katori et al., 2006)
- BMW model (Barger et al., 2007)
- puma model (Díaz et al., 2010)

this talk

Search for key signals of Lorentz violation

- sidereal variations

see Teppei Katori's talk

# Lorentz-violating Neutrino Oscillations: puma model

JSD & V.A. Kostelecký  
PLB 2011



- Isotropic (no direction dependence)
- Includes nonrenormalizable terms
- Three real parameters

## General effective hamiltonian

$$(h_{\text{eff}})_{ab} = \frac{1}{2E} (\widetilde{m}^2)_{ab} + \sum_{d \text{ odd} \geq 3} a_{ab}^{(d)} E^{d-3} + \sum_{d \text{ even} \geq 4} c_{ab}^{(d)} E^{d-3}$$

*[the model] was discovered by a systematic hunt through the jungle of possible SME-based models.”*

### Puma model

$$h_{\text{eff}} = A \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix} + B \begin{pmatrix} 1 & 1 & 1 \\ 1 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix} + C \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$A = m^2/2E, \quad B = aE^2, \quad C = cE^5$$

# Lorentz-violating Neutrino Oscillations: puma model

JSD & V.A. Kostelecký  
PLB 2011

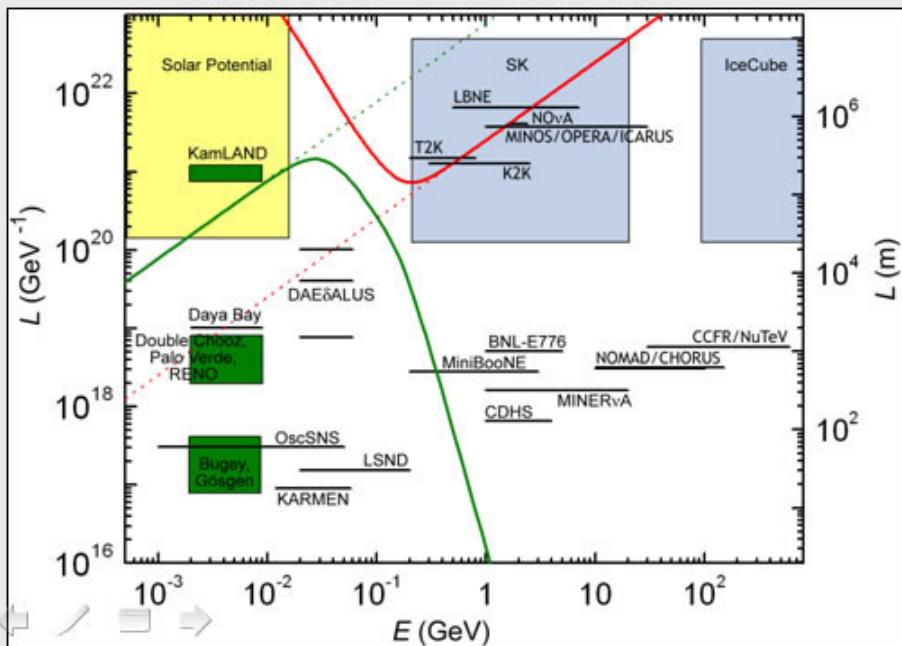
$$h_{\text{eff}} = A \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix} + B \begin{pmatrix} 1 & 1 & 1 \\ 1 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix} + C \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

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## Low energy

- mass term dominates
- symmetries: Lorentz, CPT,  $S_3$
- tri-bimaximal mixing →
- $L/E$  oscillation signature
- consistent with KamLAND data
- consistent with solar data



$$U = \begin{pmatrix} -\frac{2}{\sqrt{6}} & \frac{1}{\sqrt{6}} & \frac{1}{\sqrt{6}} \\ \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} \\ 0 & -\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

$$\begin{aligned} \Delta m_\odot^2 &\rightarrow m^2 \\ \theta_{12} &\rightarrow \text{given by texture} \end{aligned}$$

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PLB 2011

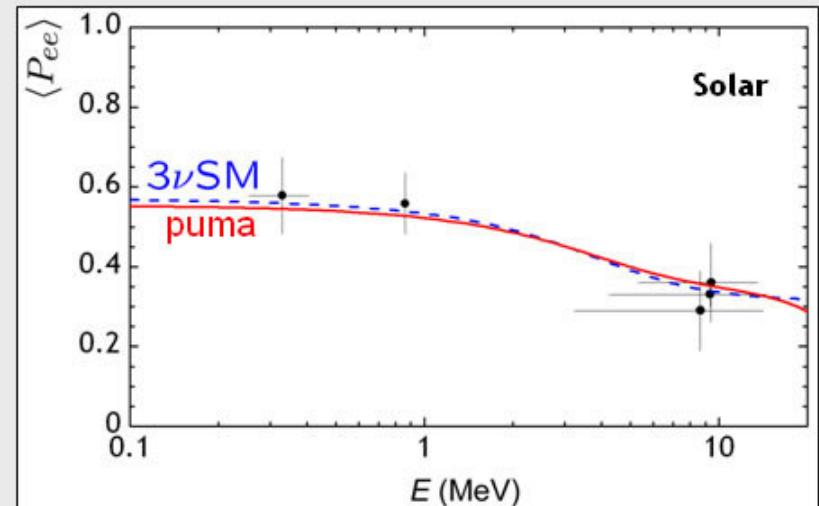
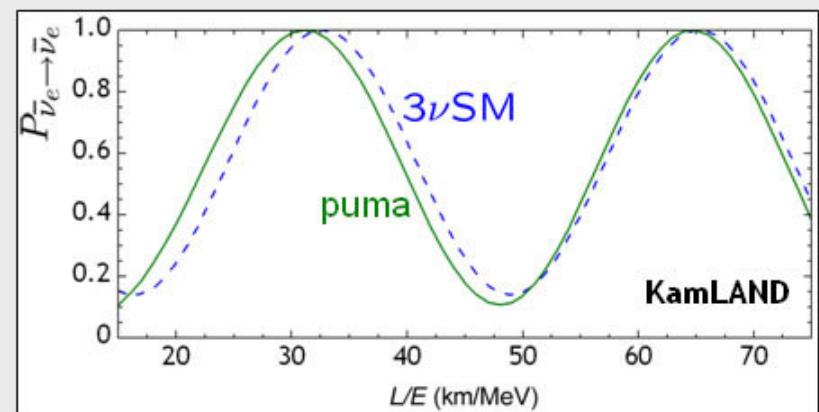
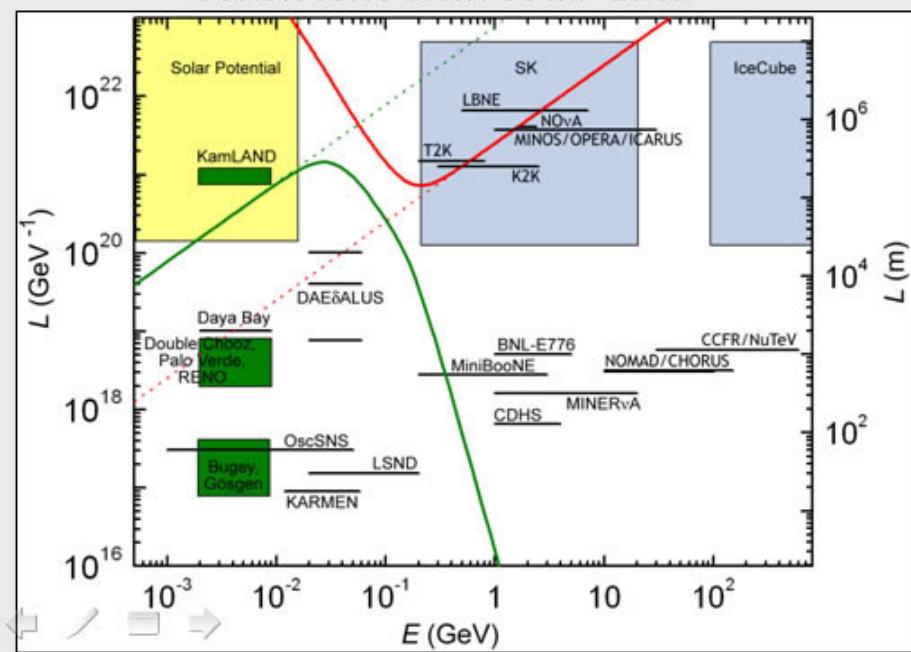
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PLB 2011

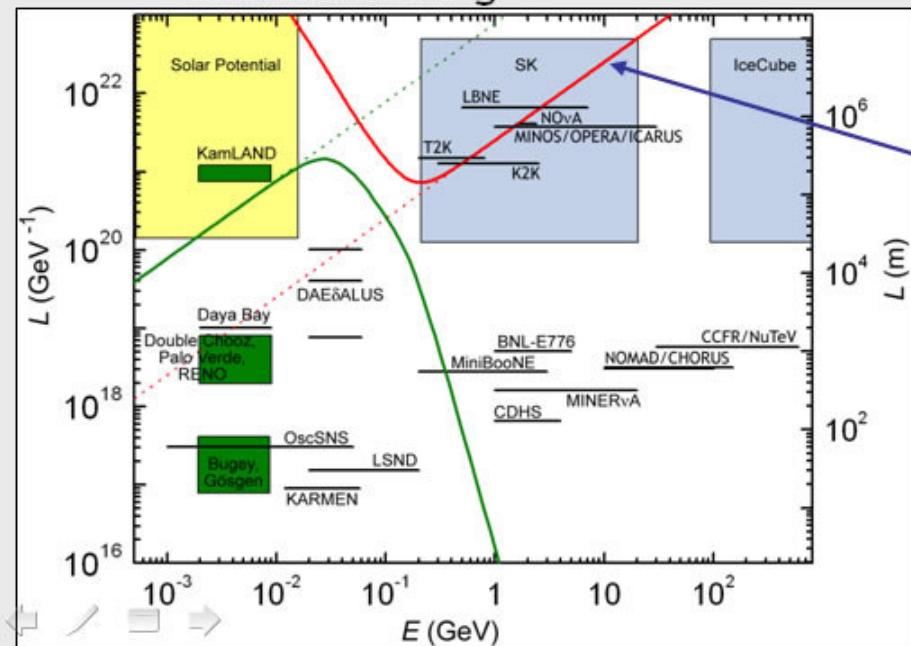
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$A = m^2/2E$ ,  
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## High energy

- no masses
- Lorentz-violating see-saw mechanism
- $L/E$  oscillation signature
- consistent with SK, K2K, MINOS, T2K
- symmetries:  $S_2$
- maximal mixing



## Lorentz-violating see-saw mechanism

$$\begin{aligned} \lambda_1 &= \frac{1}{2} \left( B + C - \sqrt{(B+C)^2 + 8B^2} \right) \\ &\approx -\frac{2B^2}{C} = -\frac{2a^2}{cE} \\ L_{31} &= \frac{\pi}{\lambda_3 - \lambda_1} \approx \frac{\pi c E}{2a^2} \end{aligned}$$

$$\begin{aligned} \Delta m_{\text{atm}}^2 &\rightarrow a^2/c \\ \theta_{23} &\rightarrow \text{texture} \end{aligned}$$

# Lorentz-violating Neutrino Oscillations: puma model

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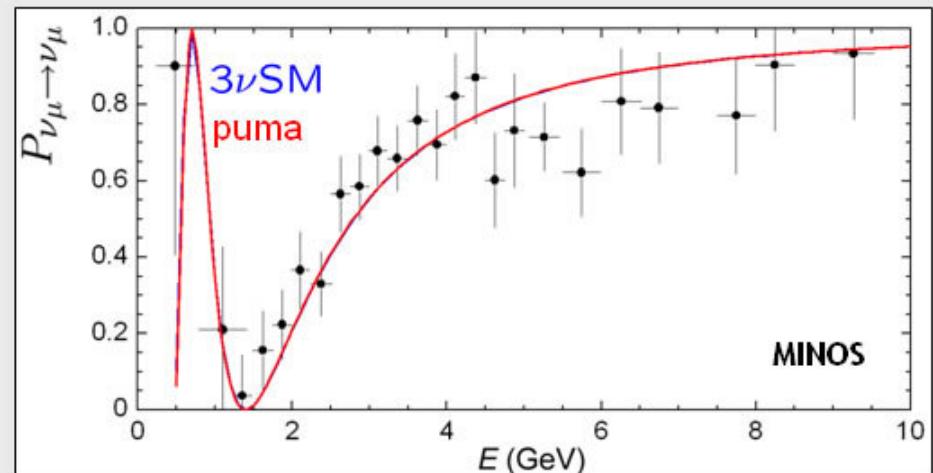
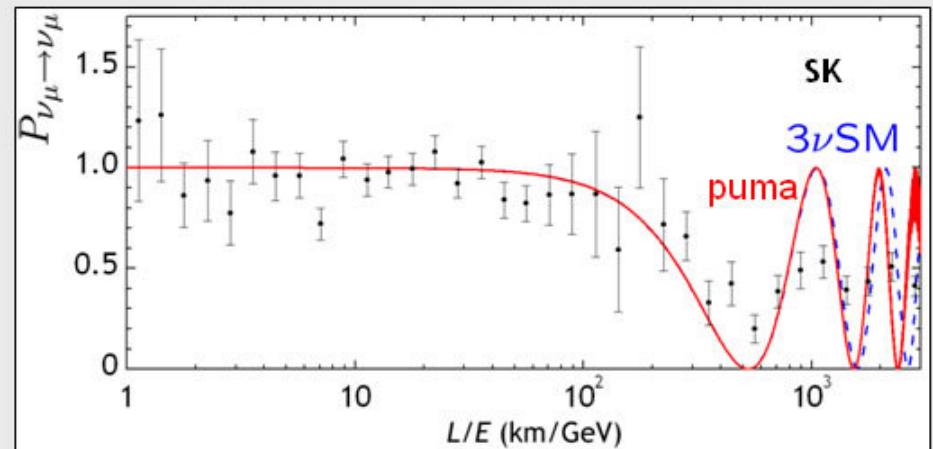
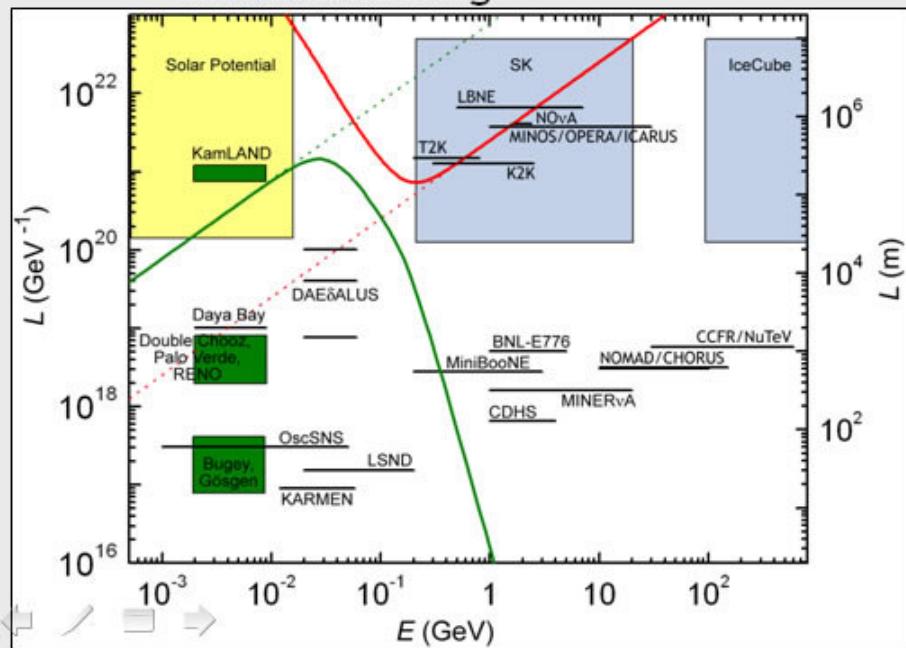
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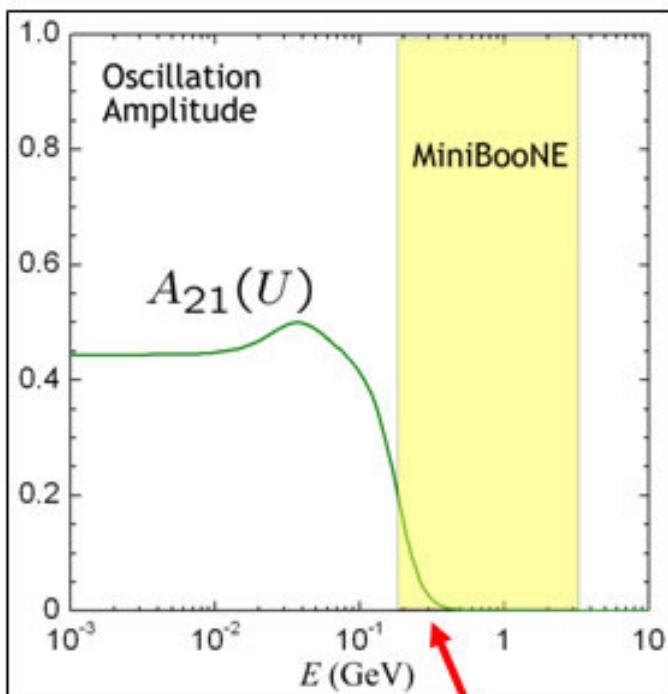
JSD & V.A. Kostelecký  
PLB 2011  
arXiv:1012.5985



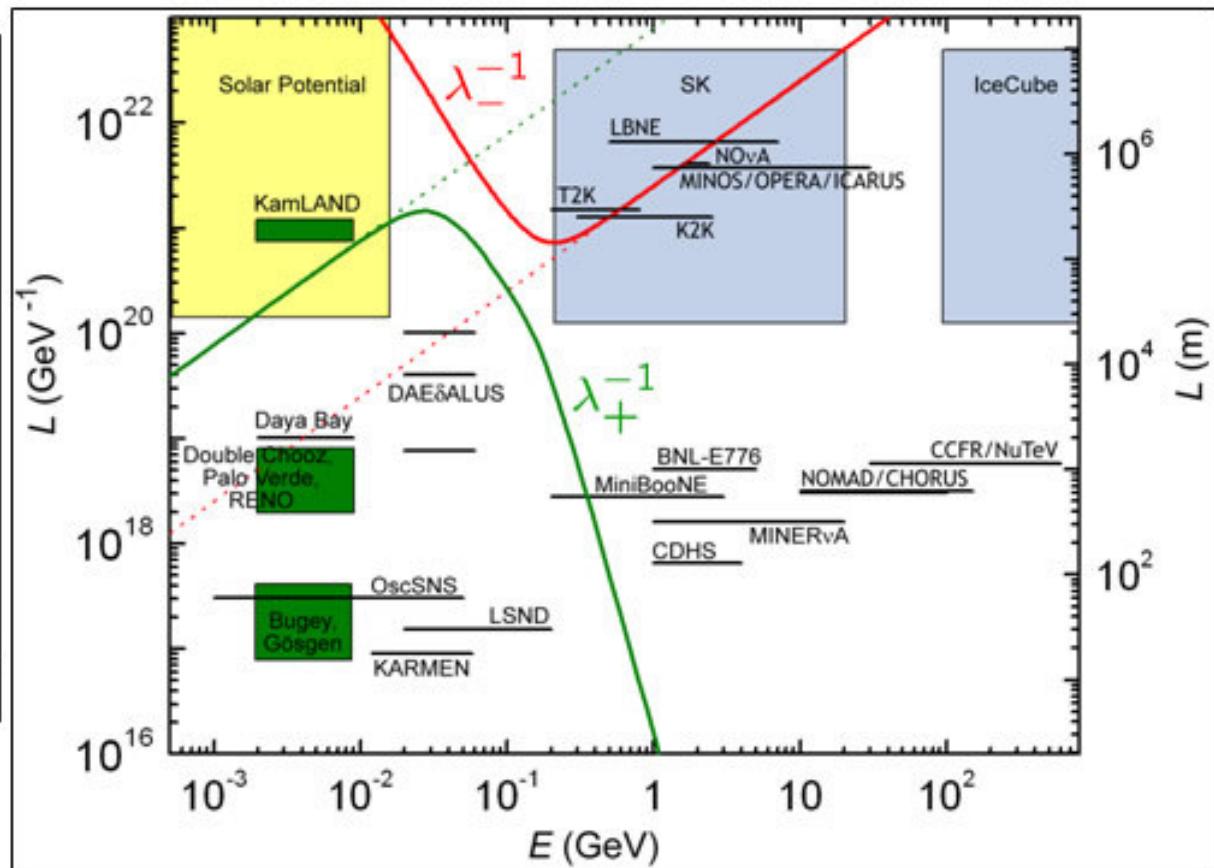
Remarkable natural feature:

Low-energy signal in MiniBooNE

$$P_{\nu_\mu \rightarrow \nu_e} \simeq A_{21}(U) \sin^2(\lambda_+ L/2)$$



signal at low energy only



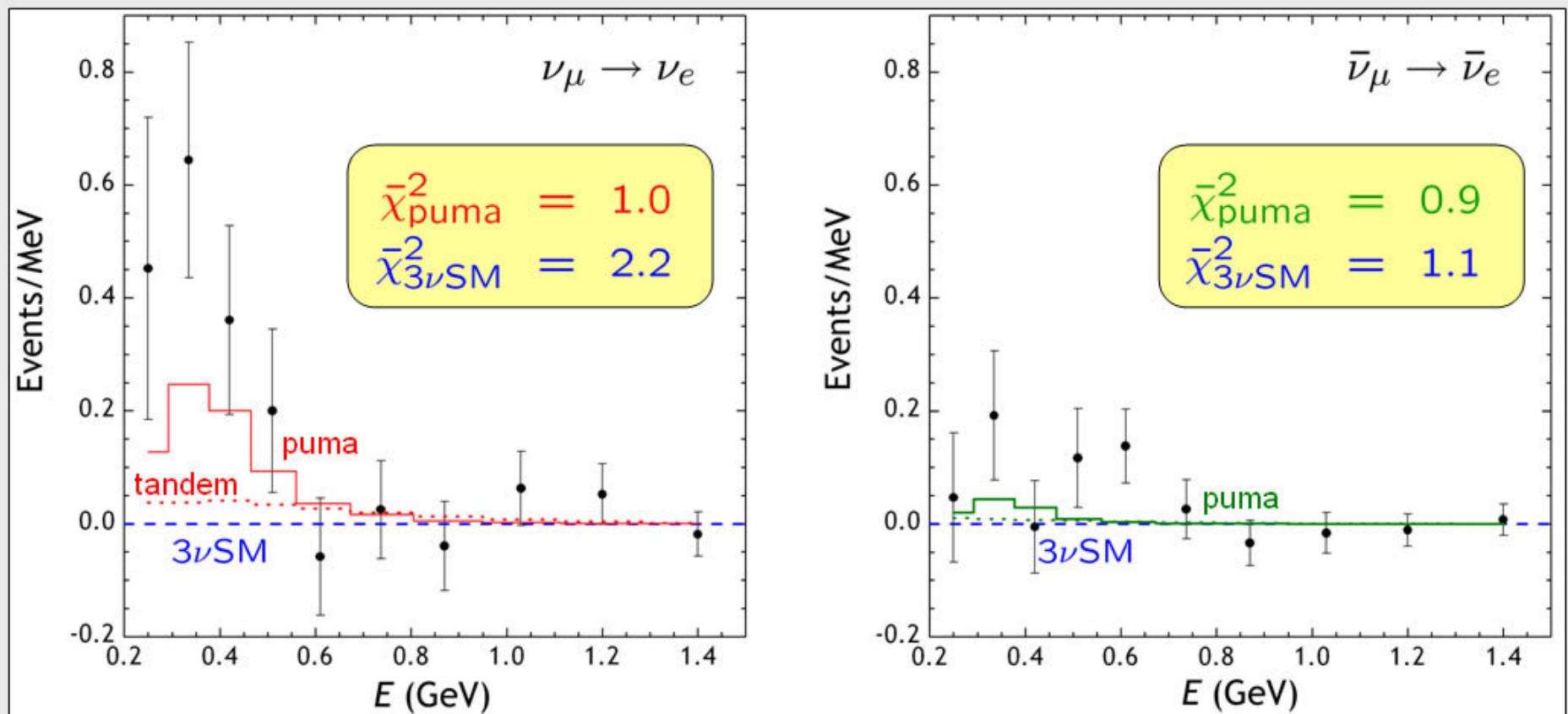
# Lorentz-violating Neutrino Oscillations: puma model

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Remarkable natural feature:

Low-energy signal in MiniBooNE



Proposal #1: MiniBooNE could use data for this one-parameter fit

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# Lorentz-violating Neutrino Oscillations: puma model

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Consistency with null results

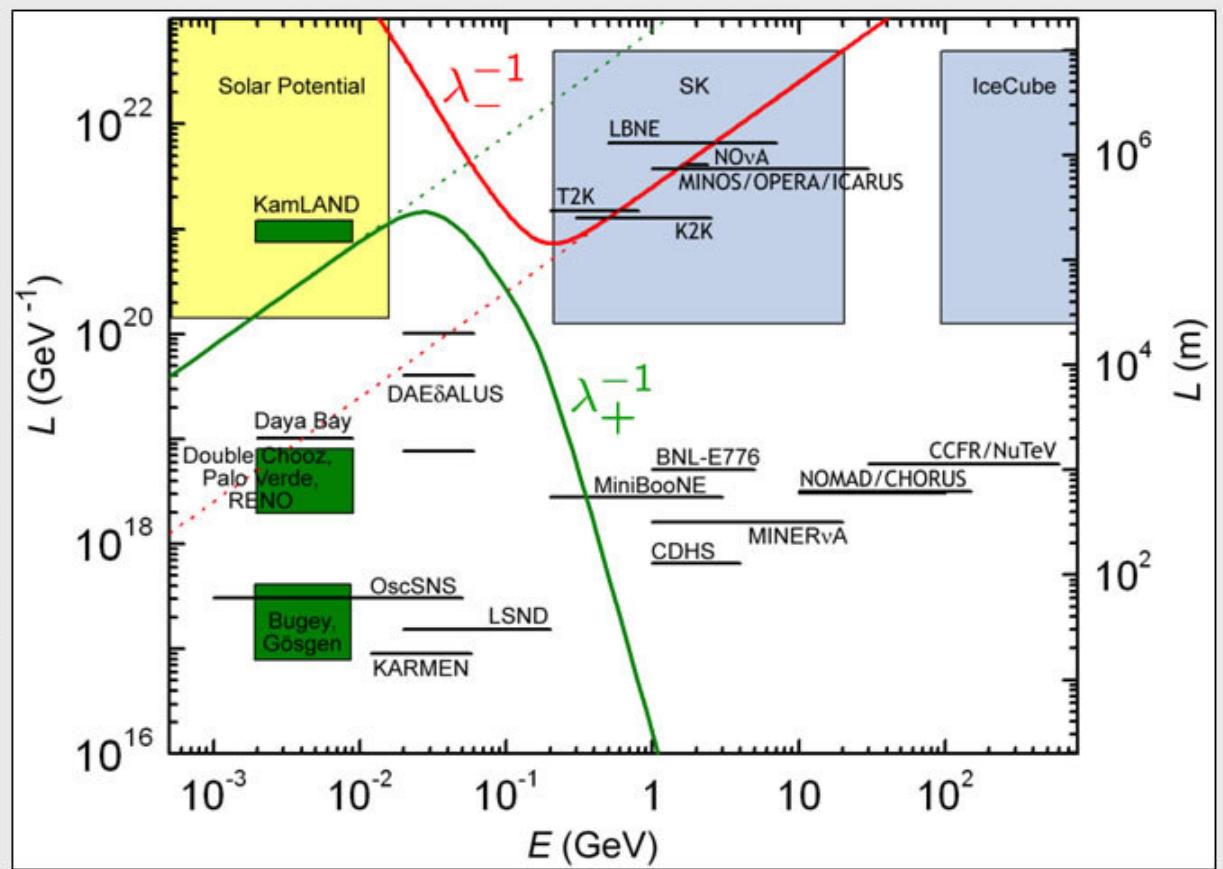
Short-baseline reactor experiments

- Bugey
- CHOOZ
- Gösgen
- Palo Verde

$$P_{\bar{\nu}_e \rightarrow \bar{\nu}_e} \simeq 1 - A_{21}(U) \sin^2(\lambda_+ L/2)$$



CHOOZ



# Lorentz-violating Neutrino Oscillations: puma model

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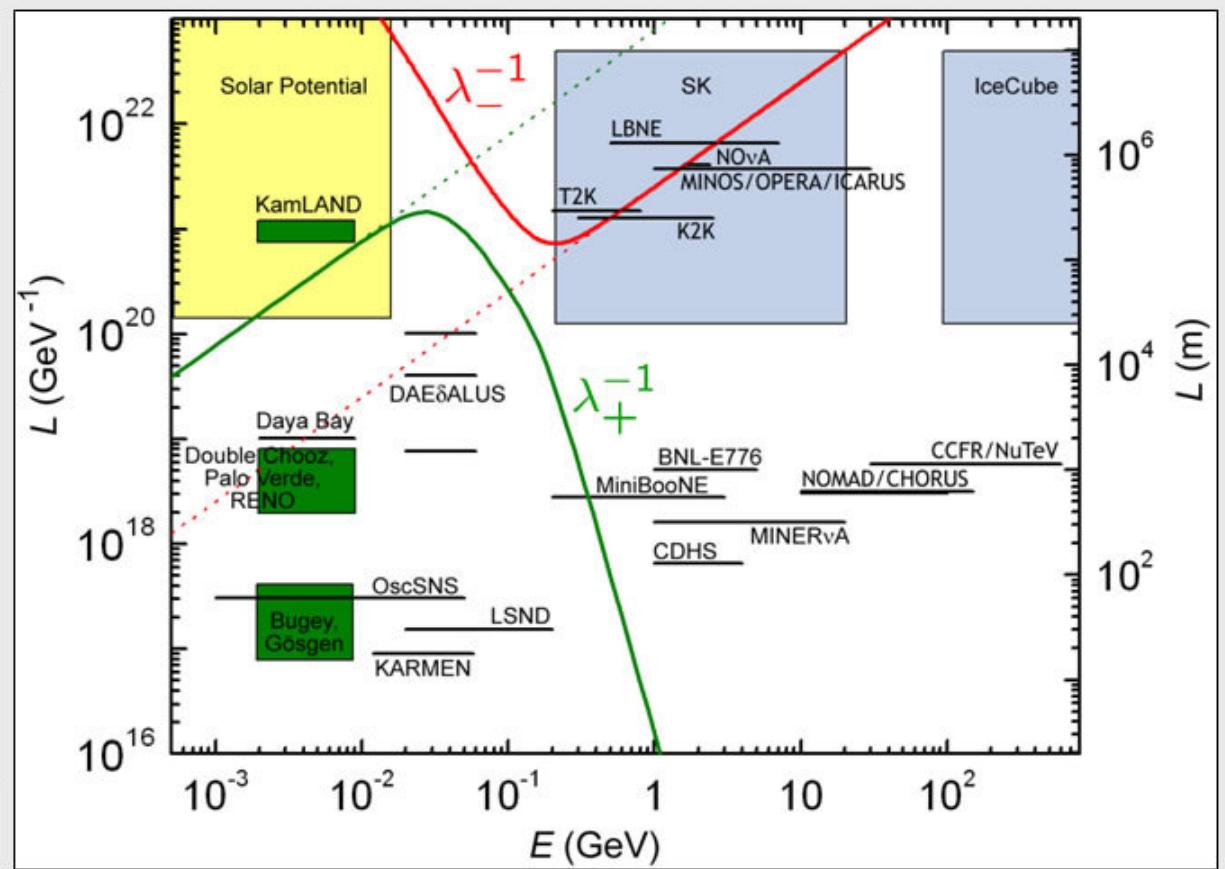
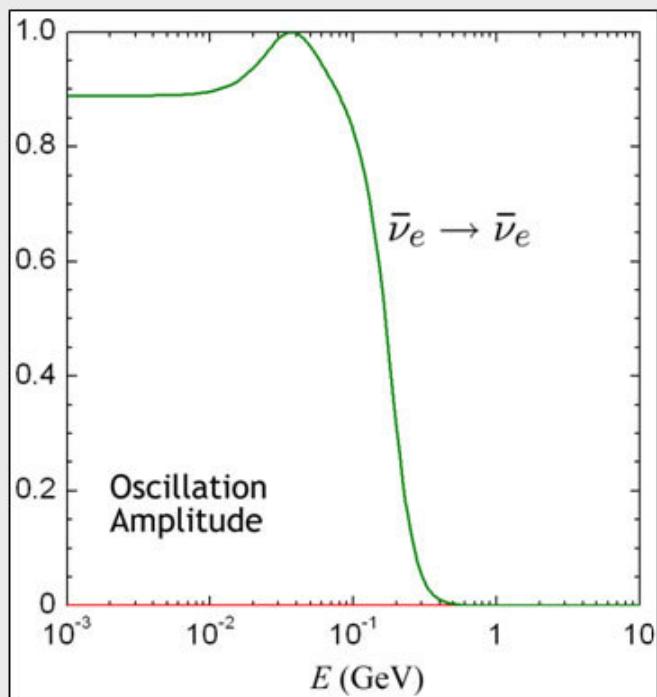


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JSD & V.A. Kostelecký  
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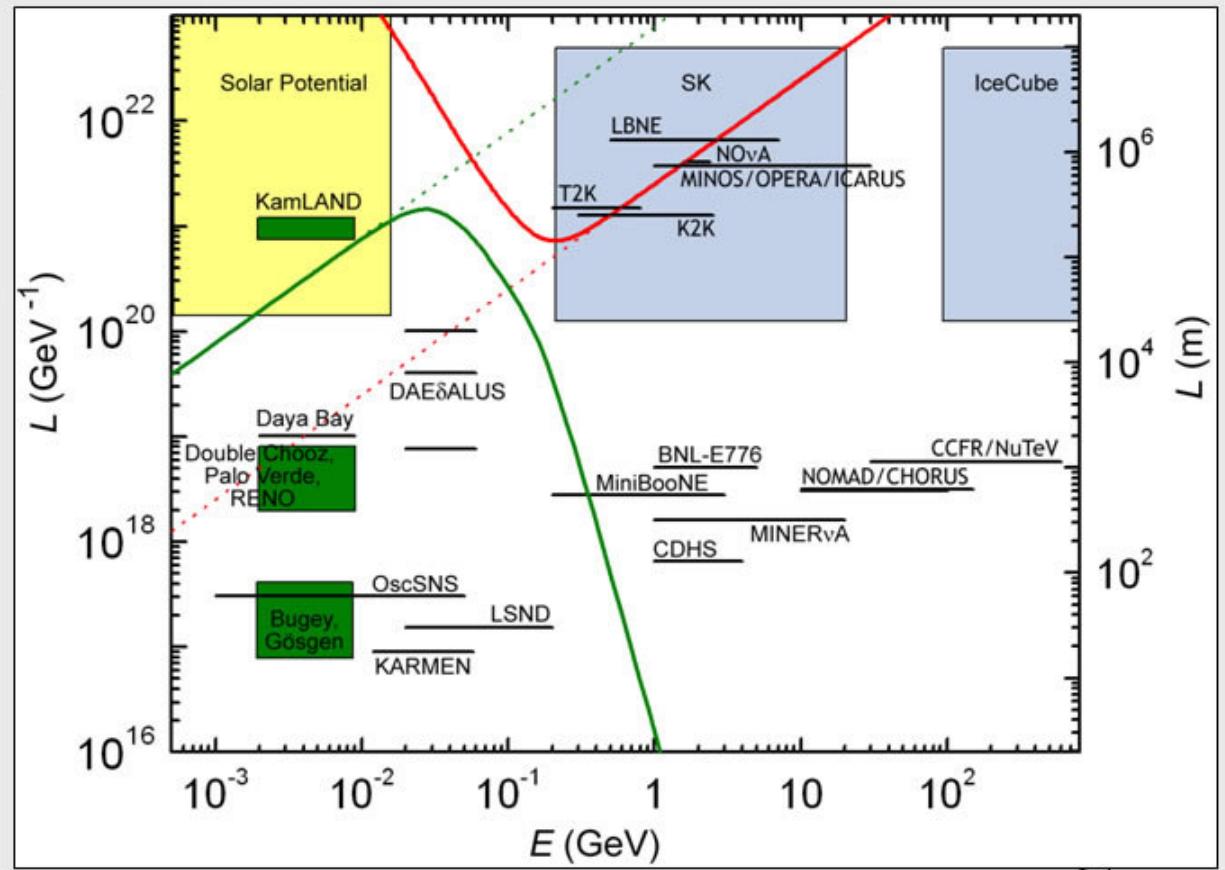
Consistency with null results

Short-baseline high-energy experiments

- BNL-E776  $\nu_\mu \rightarrow \nu_e^*$
- CCFR  $\nu_\mu \rightarrow \nu_e^*, \nu_e \rightarrow \nu_\tau^*$
- CDHS  $\nu_\mu \rightarrow \nu_\tau$
- CHORUS  $\nu_\mu \rightarrow \nu_\tau$
- NOMAD  $\nu_\mu \rightarrow \nu_\tau, \nu_e \rightarrow \nu_\tau$
- NuTeV  $\nu_\mu \rightarrow \nu_e^*$



NuTeV experiment



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# Lorentz-violating Neutrino Oscillations: puma model

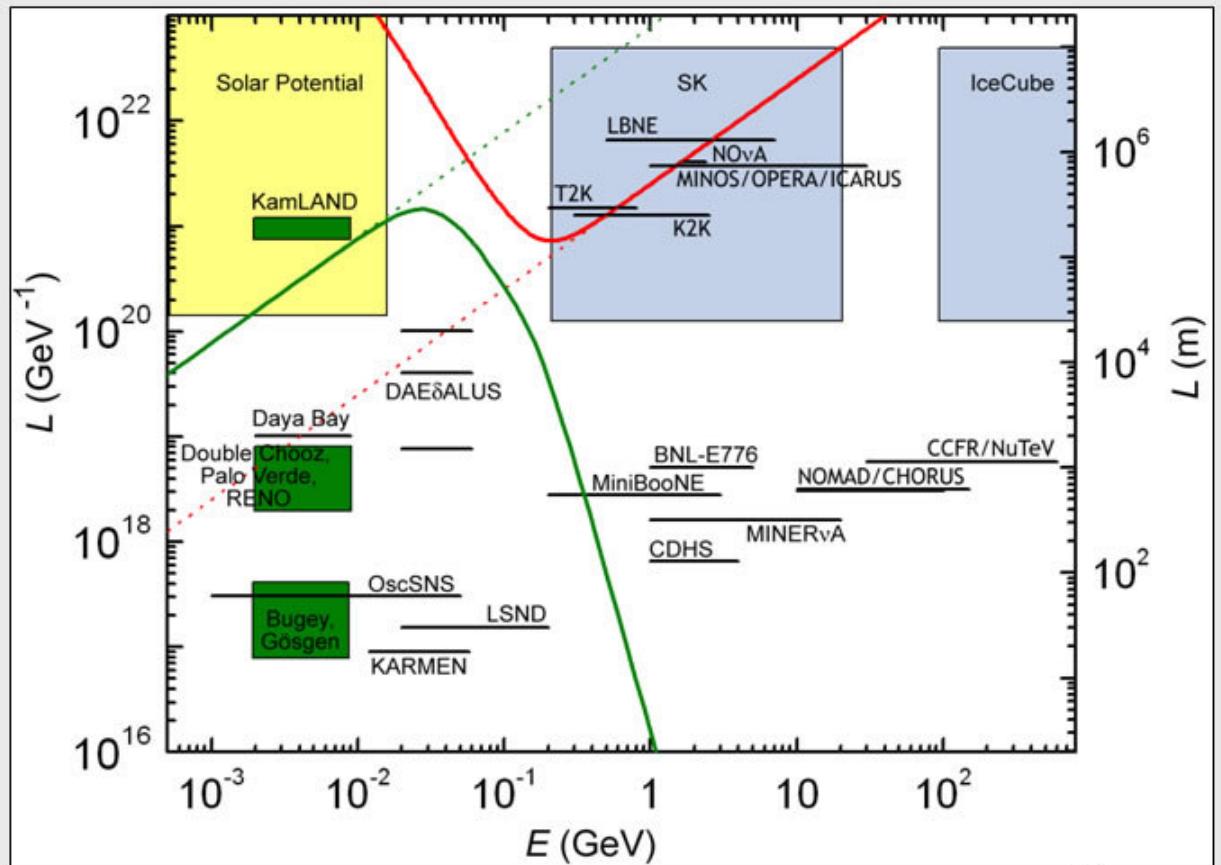
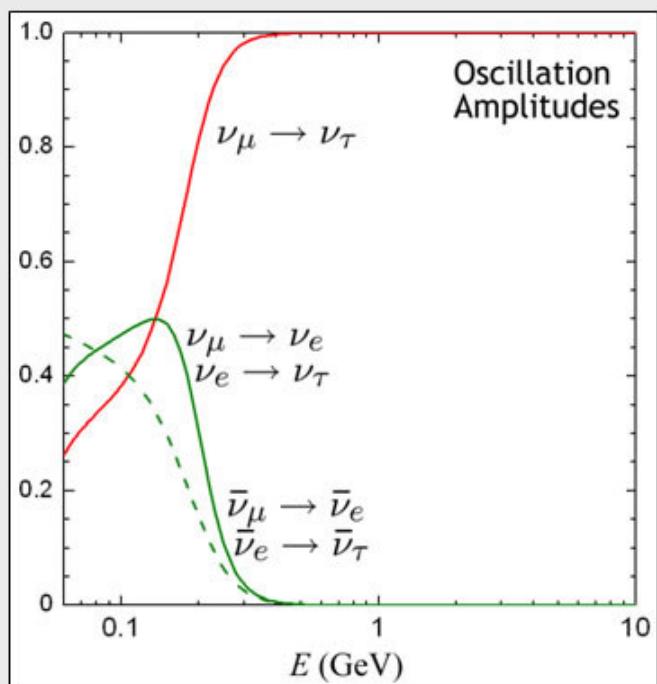
JSD & V.A. Kostelecký  
PLB 2011



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- NOMAD  $\nu_\mu \rightarrow \nu_\tau, \nu_e \rightarrow \nu_\tau$
- NuTeV  $\nu_\mu \rightarrow \nu_e^*$



## Possible extension of the puma model

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What about the MINOS anomaly?

Let us add one more CPT-even coefficient preserving the texture

### Puma\* model

$$h_{\text{eff}} = A \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix} + B \begin{pmatrix} 1 & 1 & 1 \\ 1 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix} + C \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

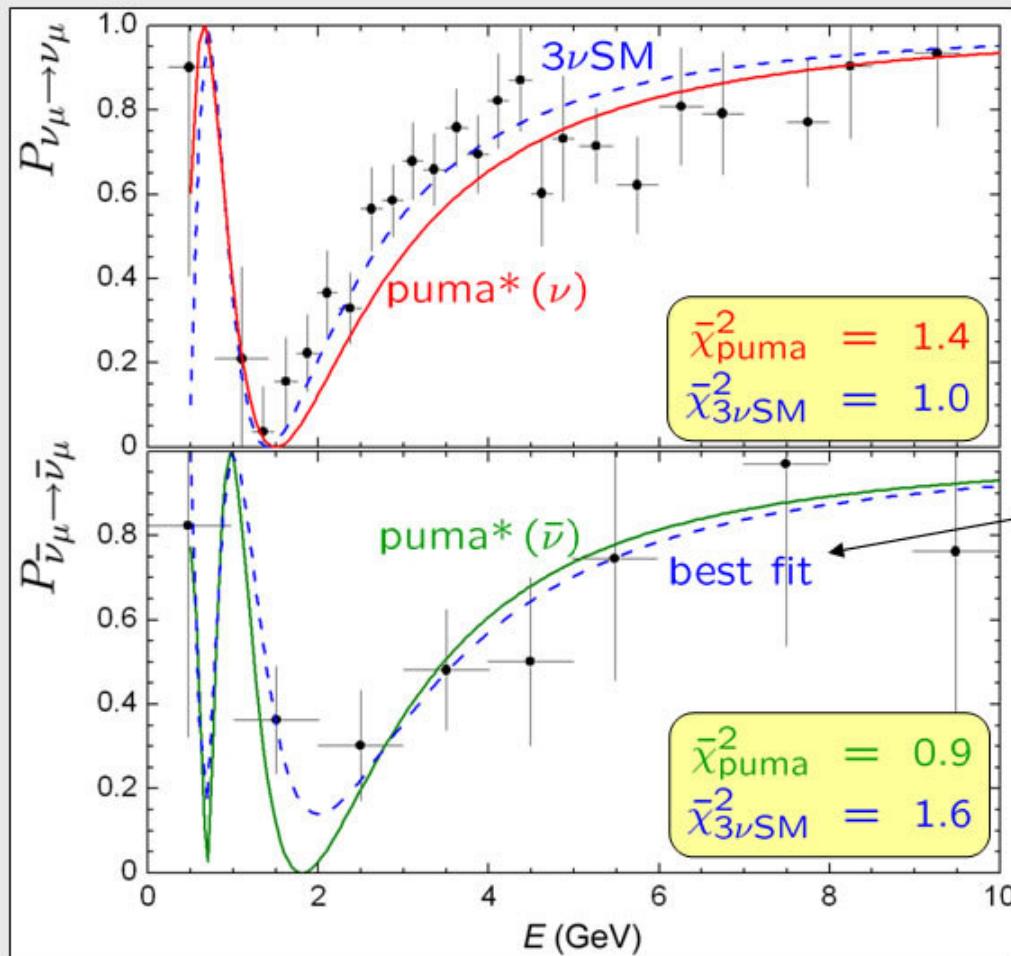
$$A = m^2/2E, \quad B = aE^2 + c'E, \quad C = cE^5 - c'E$$

# Possible extension of the puma model

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New features: the MINOS anomaly



Neutrino-antineutrino difference is produced by a CPT-odd coefficient.

There are no masses at high energy.

best fit  $\neq 3\nu\text{SM}$

Proposal #2:

MINOS could use data for this one-parameter fit

## Neutrino Oscillations: results summary

| Experiment                             | Source      | puma | 3vSM |
|--|-------------|------|------|
| Super-Kamiokande                       | Atmosphere  | ✓    | ✓    |
| KamLAND                                | Reactor     | ✓    | ✓    |
| Solar                                  | Sun         | ✓    | ✓    |
| MINOS                                  | Accelerator | ✓    | ✓    |
| LSND                                   | Accelerator | ✓*   | ✗    |
| MiniBooNE                              | Accelerator | ✓    | ✗    |
| MiniBooNE                              | Accelerator | ✓    | ✗    |
| MINOS                                  | Accelerator | ✓*   | ✗    |
| Short-baseline reactor                 | Reactor     | ✓    | ✓    |
| Short-baseline high-energy accelerator | Accelerator | ✓    | ✓    |
| Number of parameters                   |             | 3    | 4    |

(\*) extension

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## Description of anomalies: parameters

| $3\nu\text{SM}$  | puma*   |
|--|---|
| 6  | 7   |
| <p>It does not explain</p> <ul style="list-style-type: none"><li>- MiniBooNE 2007</li><li>- MiniBooNE 2010</li><li>- MINOS</li><li>- LSND</li></ul>  |  <p>consistent with everything</p> |

(\*): extension

To my knowledge no other existing model is consistent with all compelling data and all the anomalies with 7 parameters. The puma is an economical model...

## Summary

Experimental and theoretical programs are currently in progress worldwide based on the SME, a general framework for studying CPT and Lorentz violation.

A simple Lorentz- and CPT-violating texture for neutrino oscillations based on the SME is shown to be consistent with all compelling data.

This three-parameter model naturally reproduces MiniBooNE results. Direct extensions can accommodate LSND and MINOS anomalies.

Predictions of this model can be tested in the near future.

Lorentz and CPT violation offer realistic solutions to some anomalous results without introducing new particles or interactions and using only a few parameters.

Short-baseline experiments offer unique possibilities to study non-standard energy dependences beyond the Lorentz-invariant regime.